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LASER FUNDAMENTALS
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EXPERIMENTS

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LASER FUNDAMENTALS AND EXPERIMENTS

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May 1970

SWRHL

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Environmental Health Service
Bureau of Radiological Health
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FOREWORD

The Bureau of Radiological Health continues to carry out a national program designed to reduce the exposure of man to hazardous ionizing and nonionizing radiation.

Within the Bureau, the Division of Electronic Products and programs in each of the regional laboratories (1) develop and administer performance standards for radiation emissions from electronic products, (2) study and evaluate emissions of and conditions of exposure to electronic product radiation and intense magnetic fields, (3) conduct or support research, training, development and inspections to control and minimize such hazards, and (4) test and evaluate the effectiveness of procedures and techniques for minimizing such exposures. The Southwestern Radiological Health Laboratory has the responsibility for these activities in the laser area.

The Bureau publishes its findings in *Radiological Health Data and Reports* (a monthly publication), *Public Health Service numbered reports*, appropriate scientific journals, and Division and Laboratory technical reports.

The technical reports of the Southwestern Radiological Health Laboratory (SWRHL) allow comprehensive and rapid publishing of the results of intramural and contractor projects. The reports are distributed to State and local radiological health Program personnel, Bureau technical staff, Bureau advisory committee members, university radiation safety officers, libraries and information services, industry, hospitals, laboratories, schools, the press, and other interested individuals. These reports are also included in the collections of the Library of Congress and the Clearinghouse for Federal Scientific and Technical Information.

I encourage the readers of these reports to inform the Bureau of any omissions or errors. Your additional comments or requests for further information are also solicited.

John C Villforth

John C. Villforth
Director
Bureau of Radiological Health

PREFACE

Since the first laser was made operational in 1960, the laser has grown from a laboratory curiosity to a useful, flexible tool, justifying its use in many applications. One of the most common uses is that of a demonstration tool for teaching optics and wave mechanics. The laser has proven itself to be of great value in a high school or college course in basic physics and optics.

A laser can, however, be hazardous. When improperly used, for example, it can cause serious and irreversible eye damage.

The Southwestern Radiological Health Laboratory, a field laboratory of the Bureau of Radiological Health, U.S. Public Health Service, has been given the responsibility for the technical implementation of Public Law 90-602, the Radiation Control for Health and Safety Act, with respect to lasers.

This manual is the result of some of our work under the law and was prepared as a response to the increasing use of lasers for demonstration purposes in high schools and colleges, where potential exposure of large groups of unknowledgeable people is great. It is intended to serve as the text for a short course in laser fundamentals and use and is directed primarily toward the high school instructor who may use the laser in the classroom. The text is written in such a manner as to give an intuitive understanding of the device and its inherent properties. The instructor is expected to be conversant with certain of the classical elementary theories of light.

Melvin W. Carter

Dr. Melvin W. Carter, Director
Southwestern Radiological Health Laboratory

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ABSTRACT

As a result of work performed at the Southwestern Radiological Health Laboratory with respect to lasers, this manual was prepared in response to the increasing use of lasers in high schools and colleges. It is directed primarily toward the high school instructor who may use the text for a short course in laser fundamentals.

The definition of the laser, laser operation, properties of laser light, biological effects of laser light, laser applications, safety in classroom laser use, and experiment section (equipment necessary for experiments) are included in this manual.

This manual is written in a manner to give an intuitive understanding of the device and its inherent properties. The instructor is expected to be conversant with certain of the classical elementary theories of light.

Representative products and manufacturers are named for identification only and listing does not imply endorsement by the Public Health Service and the U.S. Department of Health, Education, and Welfare.

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WHAT IS A LASER?

The term "laser" is an acronym. It stands for "Light Amplification by Stimulated Emission of Radiation." Thus the laser is a device which produces and amplifies light. The mechanism by which this is accomplished, stimulated emission, was postulated by Einstein in 1917 but has only recently been applied. The light which the laser produces is unique, for it is characterized by properties which are very desirable but almost impossible to obtain by any means other than the laser.

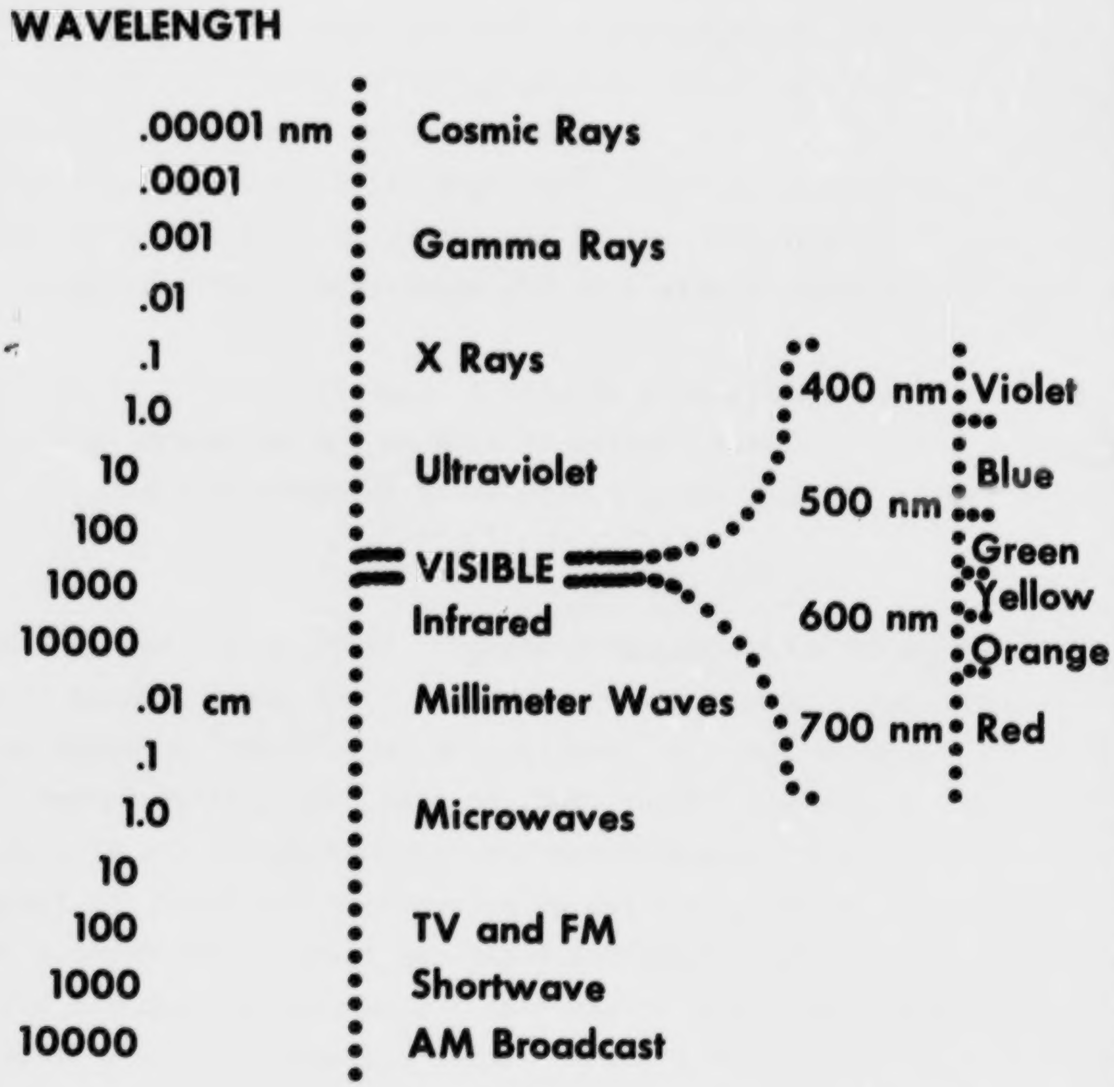
To gain a better understanding of what a laser is and what it can do, we shall start with a short review of some of the phenomena involved in laser action. A good subject with which to start is light.

A. LIGHT

Light is a form of electromagnetic energy. It occupies that portion of the electromagnetic spectrum with which man first dealt because it was visible to the human eye. Originally, the term "light" included only the visible frequencies. About 1800, however, the British-German astronomer W. Herschel placed a thermometer just beyond the blue portion of a spectrum produced by a prism using sunlight and found its temperature was raised. Later, invisible light was found on the other side of the visible spectrum. Thus it was that frequencies outside the visible range were lumped with the visible frequencies under the term "light."

Later, when x rays, radio waves and other discoveries were made, light was found to be part of a spectrum of electromagnetic radiations. The distinction between the various radiations is primarily energy which is proportional to frequency. Light is considered to be that portion of the electromagnetic spectrum having wavelengths between 100 and 10,000 nanometers (nm = 10^{-9} meters) as shown in Figure 1.

Figure 1


WAVELENGTH
.00001 nm
.0001
.001
.01
.1
1.0
10
100
1000
10000
.01 cm
.1
1.0
10
100
1000
10000
Cosmic Rays
Gamma Rays
X Rays
Ultraviolet
VISIBLE
Infrared
Millimeter Waves
Microwaves
TV and FM
Shortwave
AM Broadcast
400 nm
500 nm
600 nm
700 nm
Violet
Blue
Green
Yellow
Orange
Red

ELECTROMAGNETIC SPECTRUM

From a classical point of view, electromagnetic radiations simultaneously display two seemingly contradictory properties. Electromagnetic radiations

1. propagate through space as waves, and
2. possess a definite particulate nature, since a discrete energy and momentum are associated with them.

Each of these properties is important to the complete understanding of the behavior of all electromagnetic radiations. Both properties are combined in the current concept of light as described by quantum mechanics.

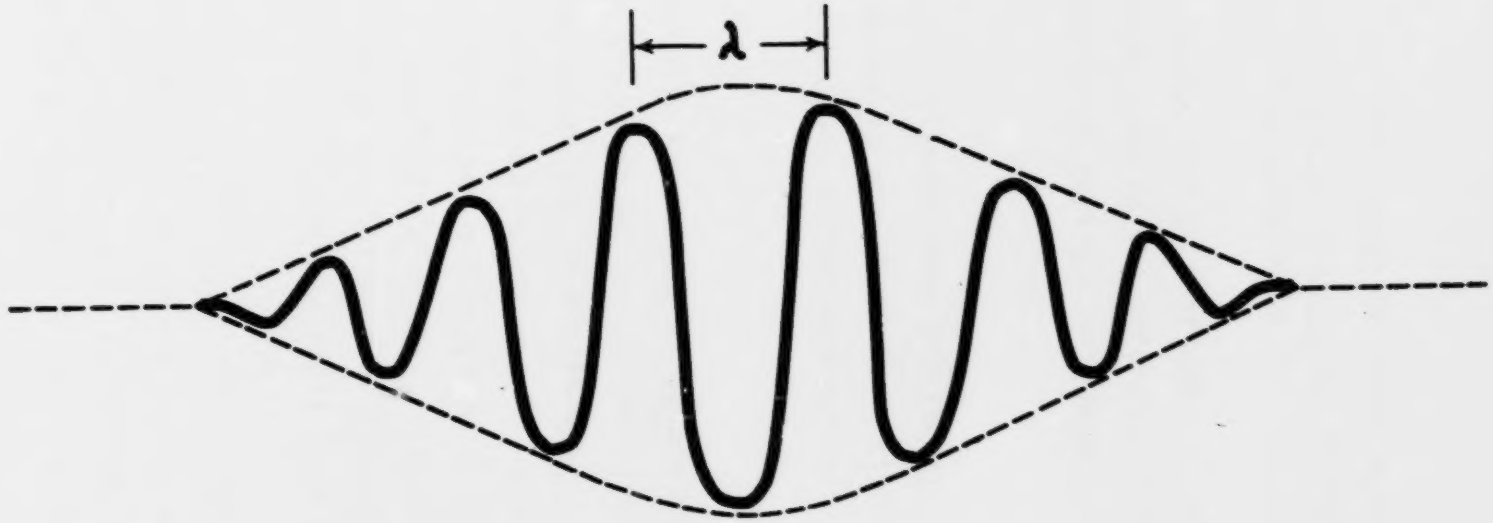
Frequently, for aid in visualizing wave behavior, light is said to move in much the same fashion as waves on a body of water. While this is not entirely true, certain characteristics are common to both types of wave motions.

The fact that a definite energy is associated with the radiation is often considered a particulate property. It is therefore difficult to visualize electromagnetic radiations as continuous waves, propagating continuously through space. One means of partially relieving this conceptual difficulty is thinking of the radiations as consisting of a limited "wave packet" which we call a "photon"(see Figure 2). The packet, or photon, is thought to move through space, thus satisfying a human need to visualize what truly cannot be visualized.

B. ELECTRON ENERGY LEVELS

Light can be produced by atomic processes, and it is these processes which are responsible for the generation of laser light. Let's look first at atomic energy levels and then see how changes in these energy levels can lead to the production of laser light.

Figure 2



REPRESENTATION OF PHOTON

A number of simplifications can be made regarding the concept of the atom. We can assume, for purposes of this discussion, that the atom consists of a small dense nucleus and one or more electrons in motion about the nucleus.

The relationship between the electrons and the nucleus is described in terms of energy levels. Quantum mechanics predicts that these energy levels are discrete. A simplified energy level diagram for a one electron atom is shown in Figure 3.

C. RADIATIVE TRANSITIONS

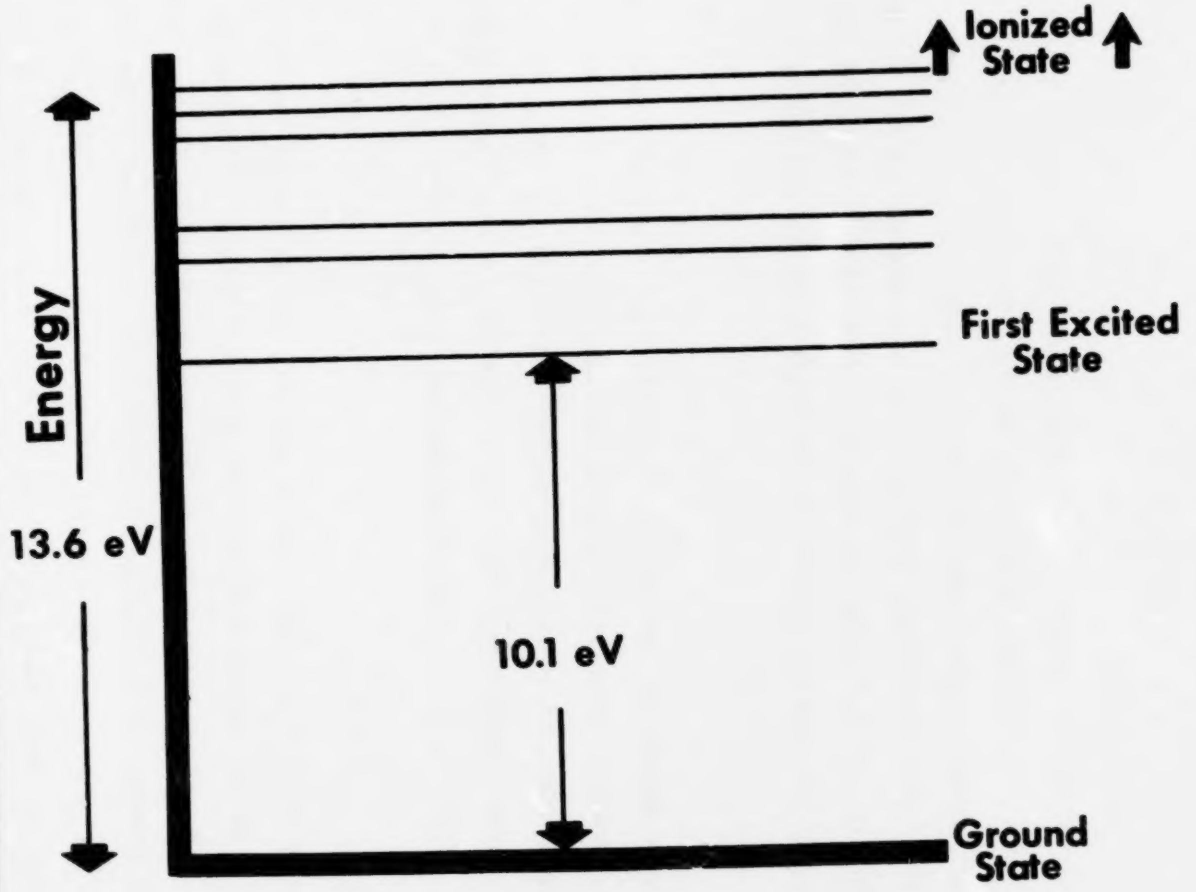
The electrons normally occupy the lowest available energy levels. When this is the case, the atom is said to be in its ground state. However, electrons can occupy higher energy levels, leaving some of the lower levels vacant. The electrons change from one energy level to another by the absorption or emission of energy. One of the ways in which an atom can change its energy state is through what is called a radiative transition.

There are three types of radiative transitions. Two of these, absorption and spontaneous emission, are quite familiar, but the third, stimulated emission, is relatively unfamiliar. It is this third type type of radiative transition that forms the basis for laser action. Each form of transition is described below.

1. Absorption

An electron can absorb energy from a variety of external sources. From the point of view of laser action, two modes of supplying energy to the electrons are of prime importance. The first of these is the transfer of all of the energy of a photon to an orbital electron. The increase in the energy of the electron causes it to "jump" to a higher energy level; the atom is then said to be in an "excited" state. It is important

Figure 3


Ionized State
First Excited State
Ground State
Energy
13.6 eV
10.1 eV

TYPICAL ENERGY LEVEL DIAGRAM

to note that an electron accepts only the precise amount of energy that will move it from one allowable energy level to another. Hence only those photons of the energy or wavelength acceptable to the electron will be absorbed.

The second means often used to excite electrons is an electrical discharge. In this technique the energy is supplied by collisions with electrons accelerated by the electric field. The result of either type of excitation is that through the absorption of energy, an electron has been placed in a higher energy level than that in which it had been residing, and the atom of which it is a part is also said to be excited.

2. Spontaneous Emission

The entire atomic structure tends to exist in the lowest energy state possible. An excited electron in a higher energy level will thus attempt to "de-excite" itself by any of several means. Some of the energy may be converted to heat. Another means of de-excitation is the spontaneous emission of a photon. The photon released by an atom as it is de-excited will have a total energy exactly equal to the difference in energy between the excited and lower energy levels. This release of a photon is called spontaneous emission. One example of spontaneous emission (and absorption) is seen in phosphorescent materials. The atoms are excited by photons of appropriate energy from the sun or a lamp. Later, in the dark, they de-excite themselves by spontaneously emitting photons of visible light. A second example is the common neon sign. Atoms of neon are excited by an electrical discharge through the tube. They de-excite themselves by the emission of photons of visible light. Note that in both of these examples the exciting force is not of a unique energy, so that the electrons may be excited to any one of several energy levels. The photons released in de-excitation may have any of these several discrete frequencies. If enough discrete frequencies are present in the appropriate distribution, the emissions may appear to the eye as "white" light.

Now let us look at the third, and probably the least familiar, type of radiative transition.

3. Stimulated Emission

In 1917, Einstein postulated that a photon released from an excited atom could, upon interacting with a second, similarly excited atom, trigger the second atom into de-exciting itself with the release of a photon. The photon released by the second atom would be identical in frequency, energy, direction, and phase with the triggering photon, AND the triggering photon would continue on its way, unchanged. Where there was one, now there are two. This is illustrated in Figure 4. These two photons could then proceed to trigger more atoms through stimulated emission.

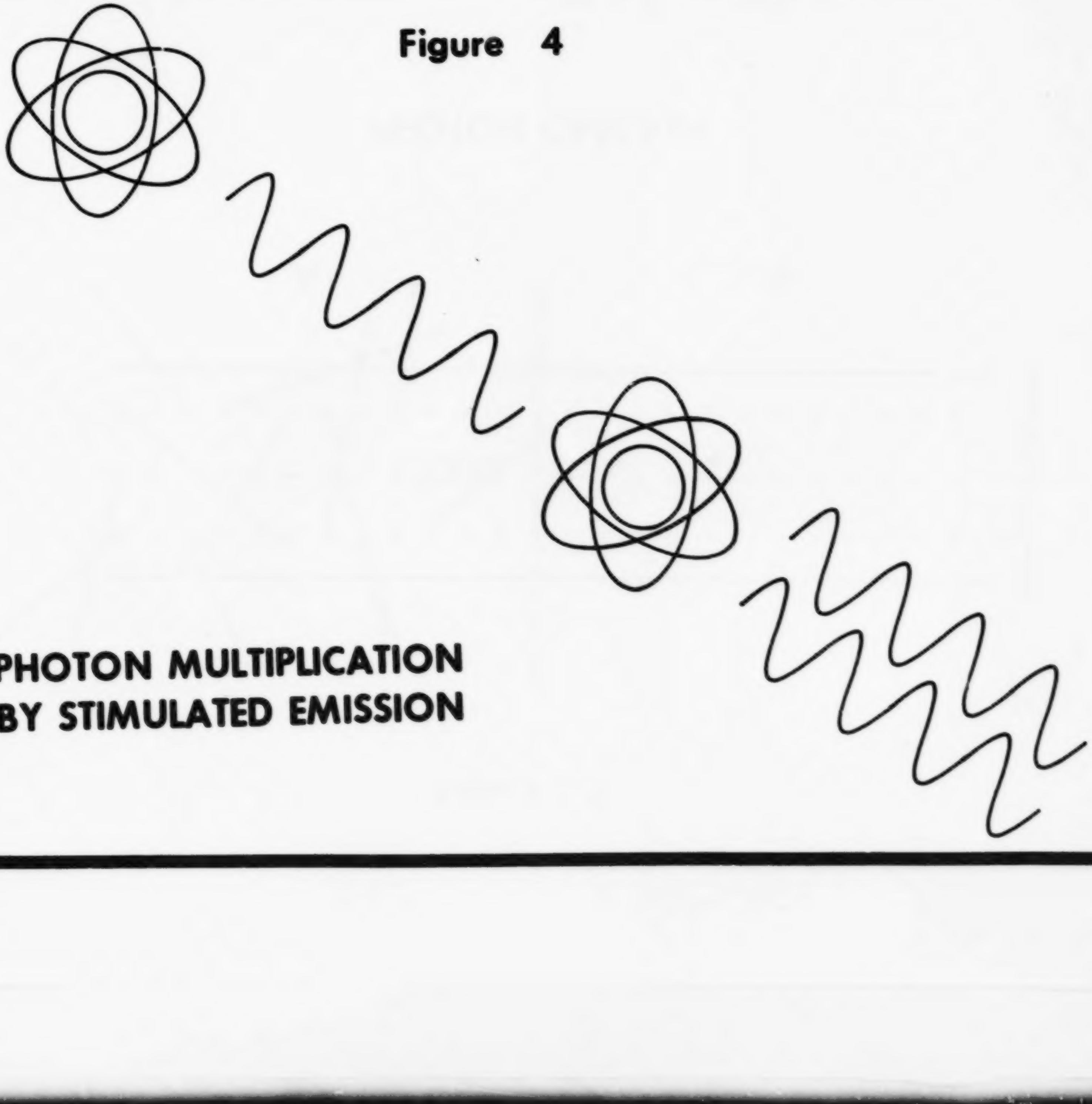
If an appropriate medium contains a great many excited atoms and de-excitation occurs only by spontaneous emission, the light output will be random and approximately equal in all directions as shown in Figure 5A.

The process of stimulated emission, however, can cause an amplification of the number of photons traveling in a particular direction -- a photon cascade -- as illustrated in Figure 5B. A preferential direction is established by placing mirrors at the ends of an optical cavity. Photons not normal (perpendicular) to the mirrors will escape. Thus the number of photons traveling along the axis of the two mirrors increases greatly and light amplification by the stimulated emission of radiation occurs.

D. POPULATION INVERSION

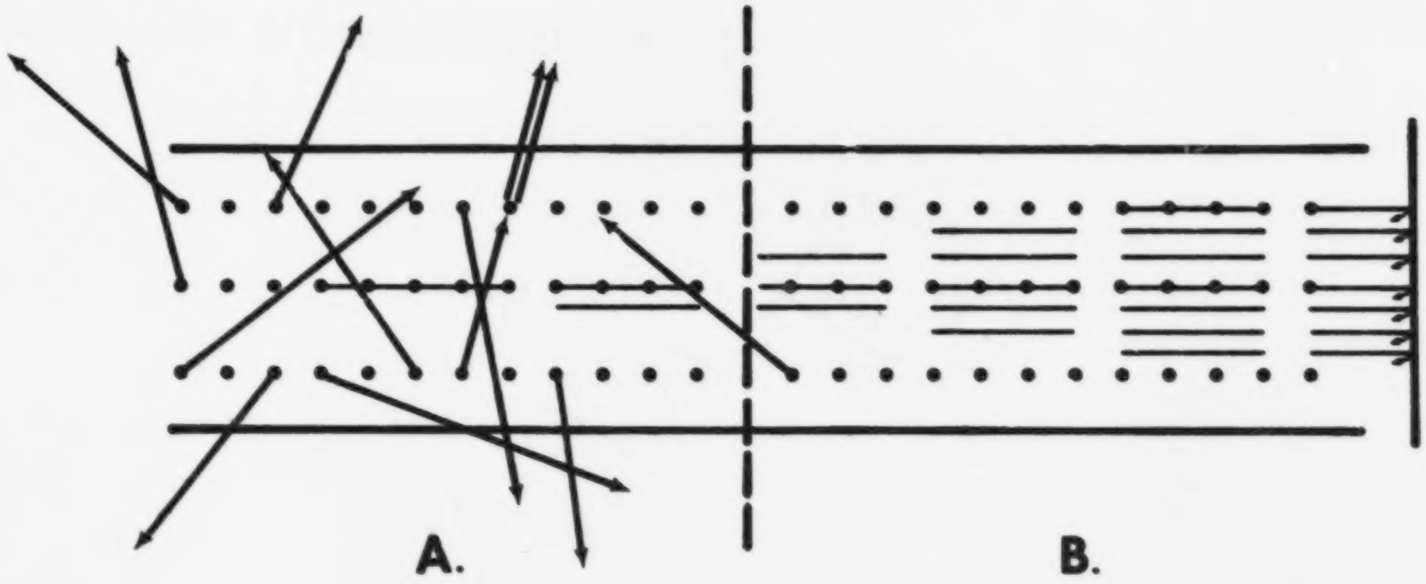
Practically speaking, the process of stimulated emission will not produce a very efficient or even noticeable amplification of light unless a condition called "population inversion" occurs. If only two of several million atoms are in an excited state, the chances of stimulated emission occurring are infinitely small. The greater the percentage of atoms in

Figure 4



PHOTON MULTIPLICATION
BY STIMULATED EMISSION

Figure 5



PHOTON CASCADE

in an excited state, the greater the probability of stimulated emission. In the normal state of matter, the population of electrons will be such that most of the electrons reside in the ground or lowest energy levels, leaving the upper levels somewhat depopulated. When electrons are excited and fill these upper levels to the extent that there are more atoms excited than not excited, the population is said to be inverted. This is illustrated in Figure 6.

Figure 6

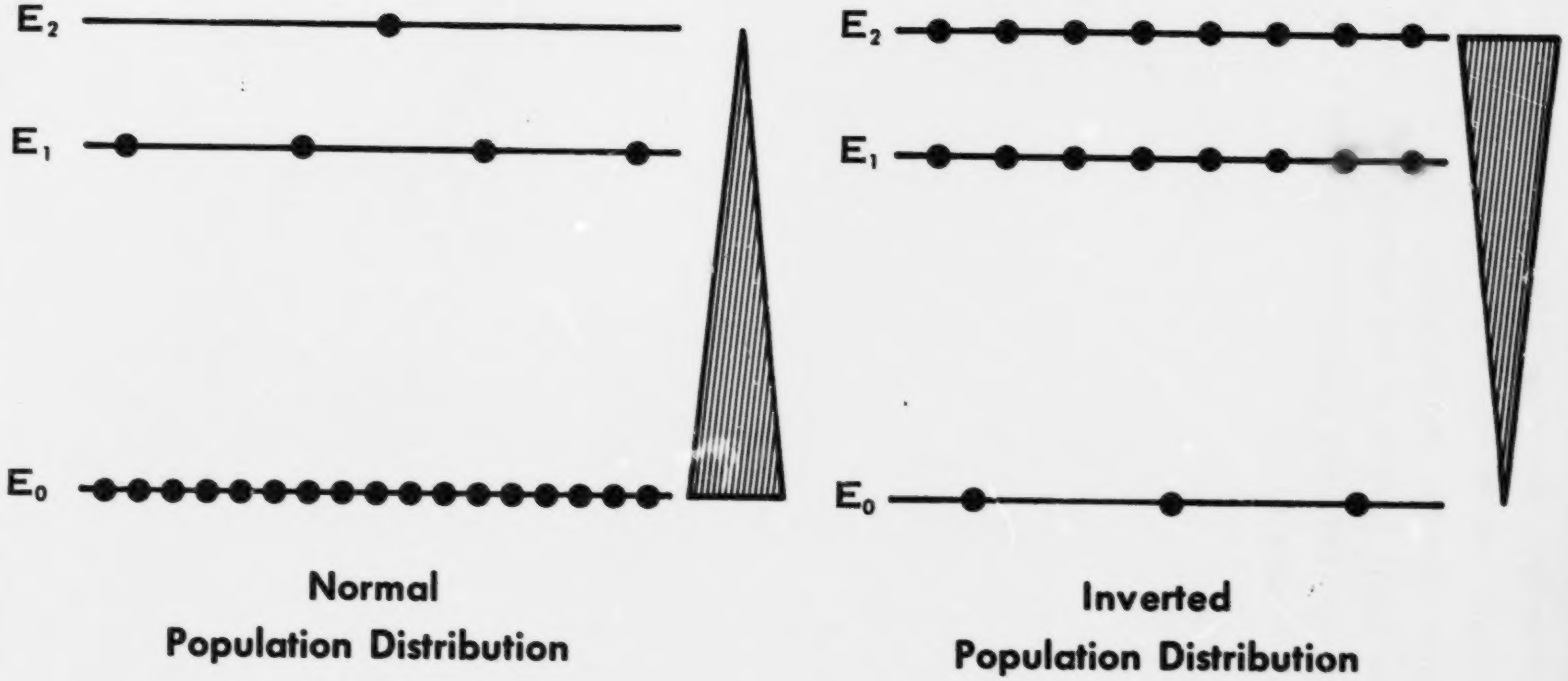

E_2
E_1
E_0
Normal
Population Distribution
E_2
E_1
E_0
Inverted
Population Distribution

ILLUSTRATION OF POPULATION INVERSION

HOW DOES THE LASER OPERATE?

Now that some of the phenomena have been discussed, let us see how a laser is constructed and how it operates. Three components are necessary: (1) an active lasing medium; (2) an input energy source (called the "pump"), and (3) an optical cavity.

A. THE LASING MEDIUM

Lasers can be classified according to the state of their lasing media. Four common families of lasers are presently recognized.

Solid state lasers employ a lasing material distributed in a solid matrix. One example is the ruby laser, using a precise amount of chromium impurity distributed uniformly in a rod of crystalline aluminum oxide. The output of the ruby is primarily at a wavelength of 694.3 nm, which is deep red in color.

Gas lasers use a gas or a mixture of gases within a glass tube. Common gas lasers include the He-Ne laser, with a primary output of 632.8 nm and the CO_2 laser, which radiates at 10,600 nm, in the infrared. Argon and krypton lasers, with outputs in the blue and green regions, are becoming quite common. Even water vapor can be made to yield a laser output in the infrared.

Liquid lasers are relatively new, and the lasing medium is usually a complex organic dye. The most striking feature of the liquid lasers is their "tunability". Proper choice of the dye and its concentration allows light production at almost any wavelength in or near the visible spectrum.

Semi-conductor lasers are not to be confused with solid state lasers. Semi-conductor devices consist of two layers of semi-conductor material sandwiched together. One material consists of an element with a surplus of electrons, the other with an electron deficit. Two outstanding characteristics of the semi-conductor laser are its high efficiency and small size. Typical semi-conductor lasers produce light in the red and infrared regions.

B. PUMPING METHODS

Laser action can occur only when a population inversion has been established in the lasing medium. This population inversion can be established by pumping energy into the lasing medium. Several methods of pumping are commonly used. Optical pumping is employed in solid state and liquid lasers. A bright source of light is focused on the lasing medium. Those incident photons of correct energy are absorbed by the electrons of the lasing material and cause the latter to jump to a higher level. Xenon flashtubes similar to strobe lights used in photography, but more powerful, are commonly used as optical pumps for solid state lasers. Liquid lasers are usually pumped by a beam from a solid state laser.

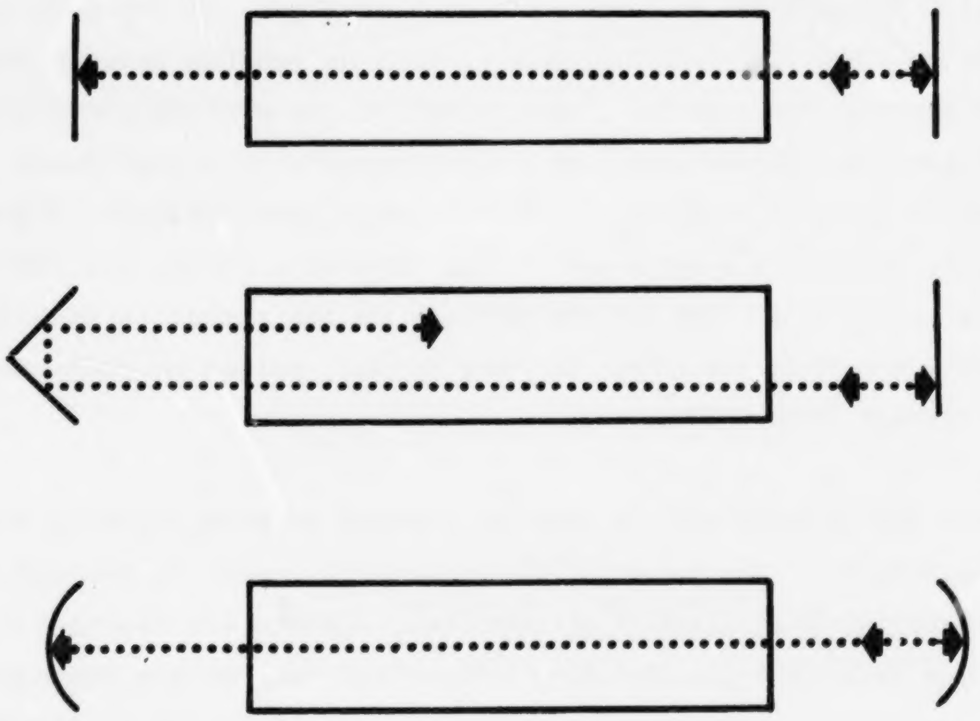
Electron collision pumping is utilized in gas lasers. An electrical discharge issent through the gas-filled tube. The electrons of the discharge lose energy through collisions with gas atoms or molecules and the atoms or molecules that receive energy are excited. Electron collision pumping can be done continuously and can therefore lead to a continuous laser output.

C. OPTICAL CAVITIES

Once the lasing medium has been pumped and a population inversion obtained, lasing action may begin. If, however, no control were placed over the direction of beam propagation, photon beams would be produced in all directions. This is called superradiant lasing.

The direction of beam propagation can be controlled by placing the lasing medium in an optical cavity formed by two reflectors facing each other along a central axis (Figure 7).

Figure 7



OPTICAL CAVITIES

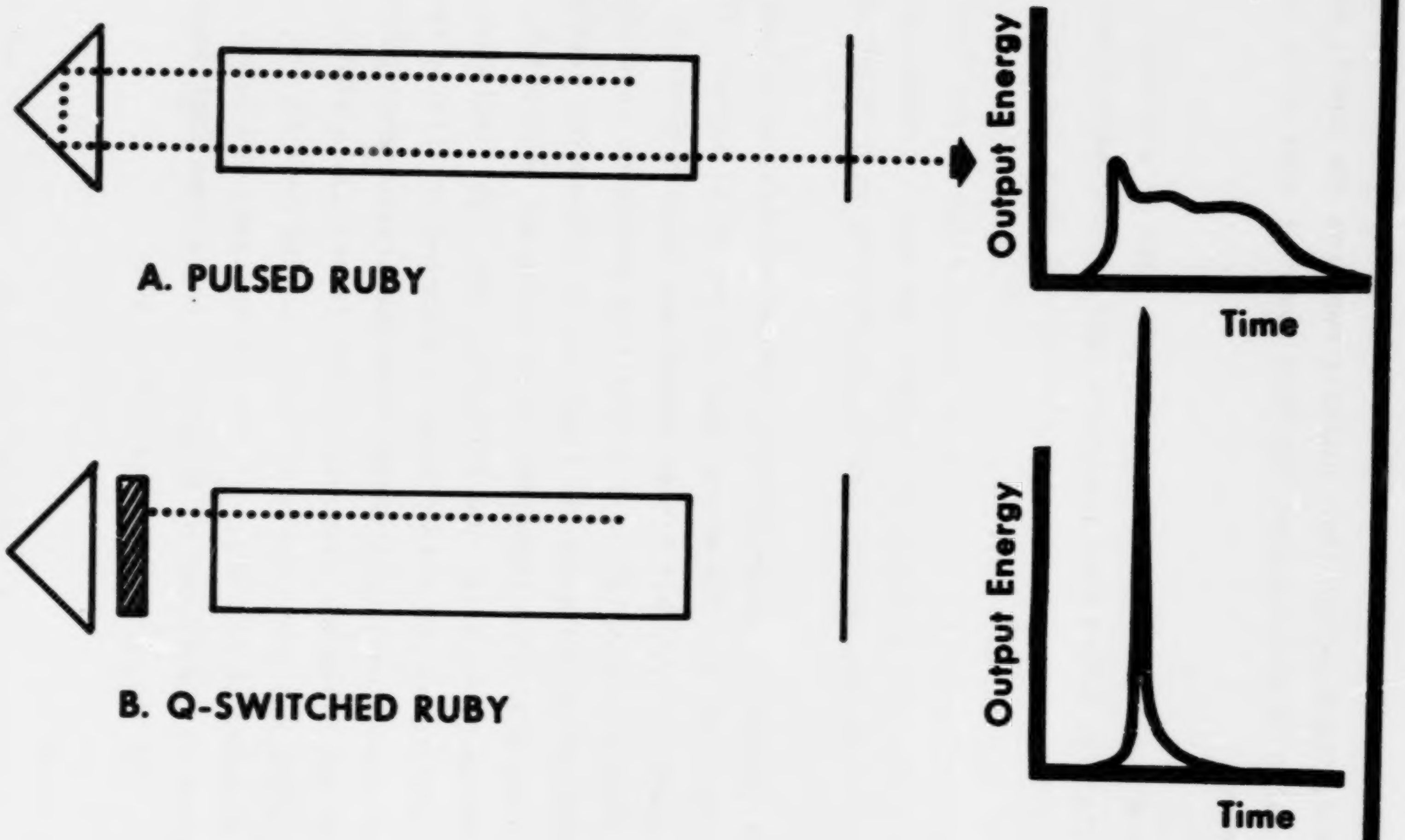
Photon beams which are produced along the cavity axis are reflected 180° at each reflection and travel once more through the lasing medium causing more stimulated emission. Thus, the beam grows in magnitude with each traverse of the lasing medium.

Since the reflectors are not 100 percent reflective some photons are lost by transmission through the mirrors with each passage. If the pumping is continuous, a state of equilibrium will soon be reached between the number of photons produced by atoms raised to the excited state and the number of photons emitted and lost. This results in a continuous laser output and is usually used only with low power input levels. Higher power inputs usually are achieved in the form of a pulse, and the output is also in pulse form. One of the mirrors in the system is usually made more transparent than the other and the output, pulsed or continuous, is obtained through this reflector.

Q-switching (or Q-spoiling) is used to produce an exceptionally high-power output pulse. The term "Q" as applied to lasers is derived from the more familiar Q of electrical circuits. Lasers are resonant cavities and in a similar way, many electrical devices are resonant. The Q is a numerical index of the ability of the resonant cavity to store energy at the output frequency. The higher the Q, the more effective the power concentration at the resonant frequency. Q-switching in lasers refers to the method of laser operation in which the power of the laser is concentrated into a short burst of coherent radiation. A Q-switch is a device which interrupts the optical cavity for a short period of time during pumping. A schematic of a Q-switched solid state laser is shown in Figure 8.

Lasing action normally begins as soon as a population inversion is achieved and continues as long as pumping action maintains the inversion. The Q-switch interrupts the optical cavity and reduces the losses due to

Figure 8


Output Energy
Time
A. PULSED RUBY
Output Energy
Time
B. Q-SWITCHED RUBY

Q SWITCH AND PULSE OUTPUT DIAGRAM

lasing until pumping can achieve a greater population inversion, say 70 to 80 percent, the Q switch then suddenly restores the cavity and the resulting pulse is much shorter and more powerful than would normally be achieved.

One example of a Q switch is the Pockel's cell, made of a crystal of ammonium or potassium dihydrogen phosphate (ADP or KDP) sandwiched between two crossed polarizers. In its de-energized state the crystal will not affect polarized light. When an electric field is applied across the crystal, however, the plane of polarization of the incident light is rotated by 90°, allowing it to pass the second crossed polarizer. This completes the optical cavity and results in a "giant pulse".

Reflectors may consist of plane mirrors, curved mirrors, or prisms, as shown in Figures 7 and 8. The mirror coating may be of silver, if laser output power is low, but higher powers may require dichroic material. A dichroic material is a crystalline substance in which two preferred states of polarization of light may be propagated with different velocities and, more important, with different absorption. By appropriate choice of material and thickness, the light impinging upon the dichroic coating may be either totally absorbed or totally reflected. The first ruby lasers were constructed with the crystal ends polished optically flat and silvered. Semi-conductor lasers use a similar technique. Gas lasers may use mirrors as seals for the ends of the gas tube or may utilize exterior mirrors. In the latter case, the tubes use end windows of glass or quartz set at Brewster's angle (see Experiment 5, Polarization), and the output is polarized light.

D. THE RUBY LASER

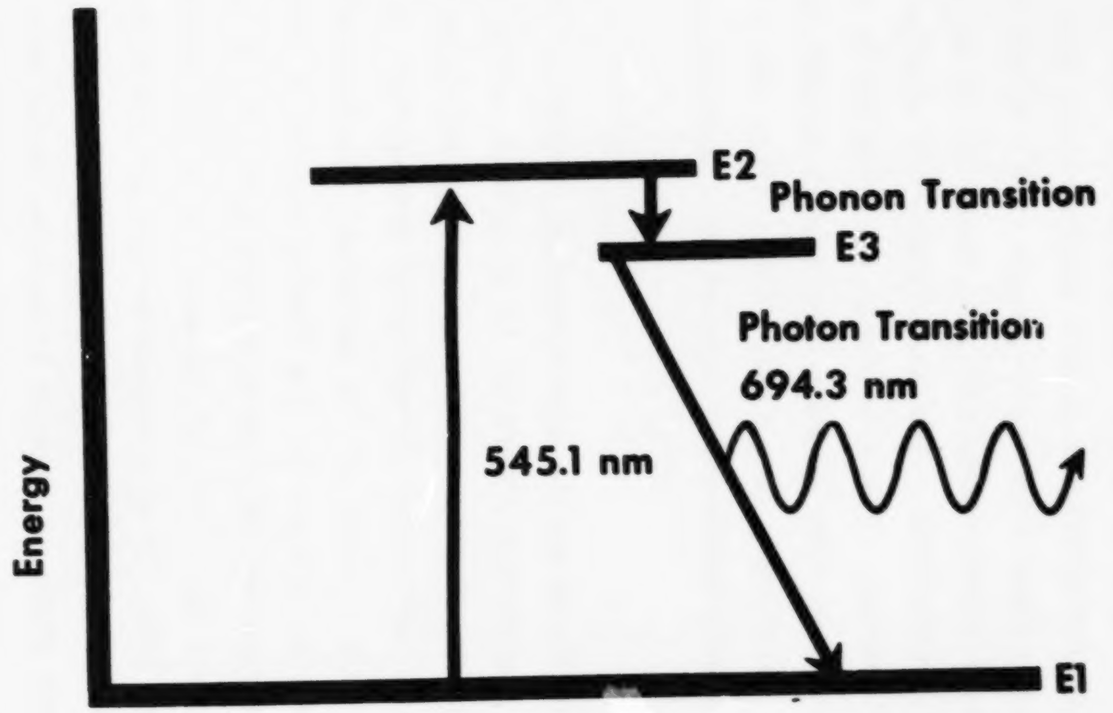
The laser first successfully operated was a ruby laser. It was constructed and operated by Dr. T. H. Maiman in 1960. Ruby is a crystal form of aluminum oxide with about 0.05 percent by weight chromium as an impurity. The chromium gives the ruby its red color and is responsible for the lasing. Chromium exhibits a 3-level energy system, as represented in Figure 9.

In a ruby laser, the electrons of chromium atoms are pumped to an excited energy level by means of a xenon flashlamp placed beside or around the ruby rod. The chromium electrons absorb photons in a band centered around 545.1 nm and are raised from their ground level to excited level E2. From here they drop almost immediately to level E3 by means of a phonon (radiationless) transition. The small amount of energy lost here is through heat and vibration. The electrons will reside in level E3 for a considerable length of time -- much less than a second -- but for an electron that is a relatively long time. Thus, since the flashlamp operates in a period of microseconds, a population inversion can be obtained.

The excited atoms begin to de-excite spontaneously, dropping from level E3 to E1, and since a population inversion is in effect, stimulated emission may begin. In any lasing medium, stimulated emission may occur in all directions and no particular direction of propagation is favored. As stated earlier, to gain control of the emission direction and increase the amount of energy within the pulse, the lasing medium is placed within an optical cavity. Photons not emitted along the axis of the cavity will pass out of the system and be lost. If, however, a photon cascade is aligned with the cavity axis, it will encounter one of the mirrors and be reflected back upon itself, pass once more through the lasing medium and trigger more excited atoms to undergo stimulated emissions. The pulse thus grows in size and on each encounter with the less reflective mirror, part of it emerges from the laser as high intensity coherent light.

The pulse from a typical ruby laser lasts only a few microseconds, since the pumping is not continuous. The flashlamp is run by a charge stored in capacitor banks, and once the lamp has flashed, the capacitors must be recharged. Pumping occurs over a few hundred microseconds and continues as long as the flashlamp is discharging.

Figure 9


E2
Phonon Transition
E3
Photon Transition
694.3 nm
545.1 nm
Energy
E1

ENERGY LEVELS OF CHROMIUM

E. THE HE-NE LASER

The most common laser used today in both industry and education is the He-Ne laser. It was first operated in 1961 by Ali Javan and has proved to be the forerunner of a whole family of gas lasers. Since gas lasers are all quite similar in construction and behavior, we shall discuss the He-Ne as representative of the group.

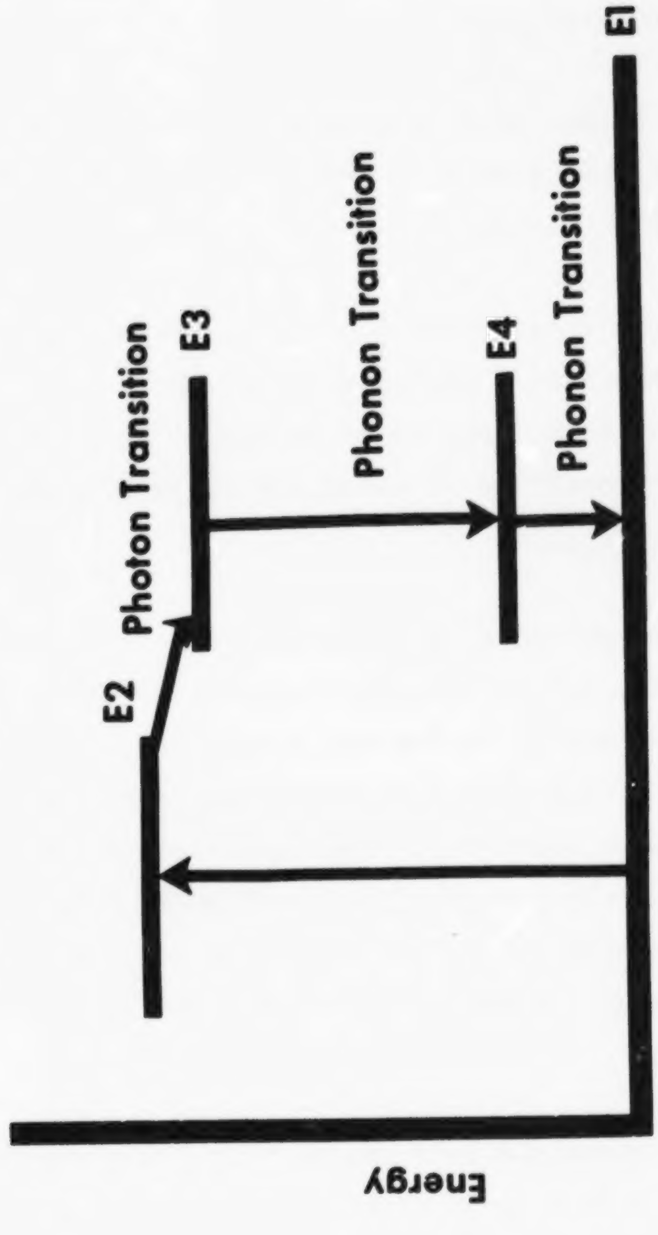
The lasing medium in the He-Ne laser is a mixture of about 90 percent helium and 10 percent neon, with neon providing the lasing action. An energy level diagram for neon is shown in Figure 10.

The 4-level system of a gas laser differs from the three-level system of chromium in that the emission of a photon does not return the atom to a ground level. Transitions from level E3 to E4 and E4 to E1 are accomplished through a phonon transition in which energy is transferred mainly through heat.

Pumping of neon to an excited state is not done directly by the energy source. Rather, indirect pumping is accomplished by exciting atoms of helium which then transfer energy to the new atoms by way of electron collision. These two gases are picked because they have electron excitation levels which are almost identical, thus facilitating the necessary energy transfer. Additionally, in the mixture of gases used, one does not need to affect a population inversion in helium in order to obtain a population inversion in neon. A more complete energy level scheme for He-Ne is shown in Figure 11.

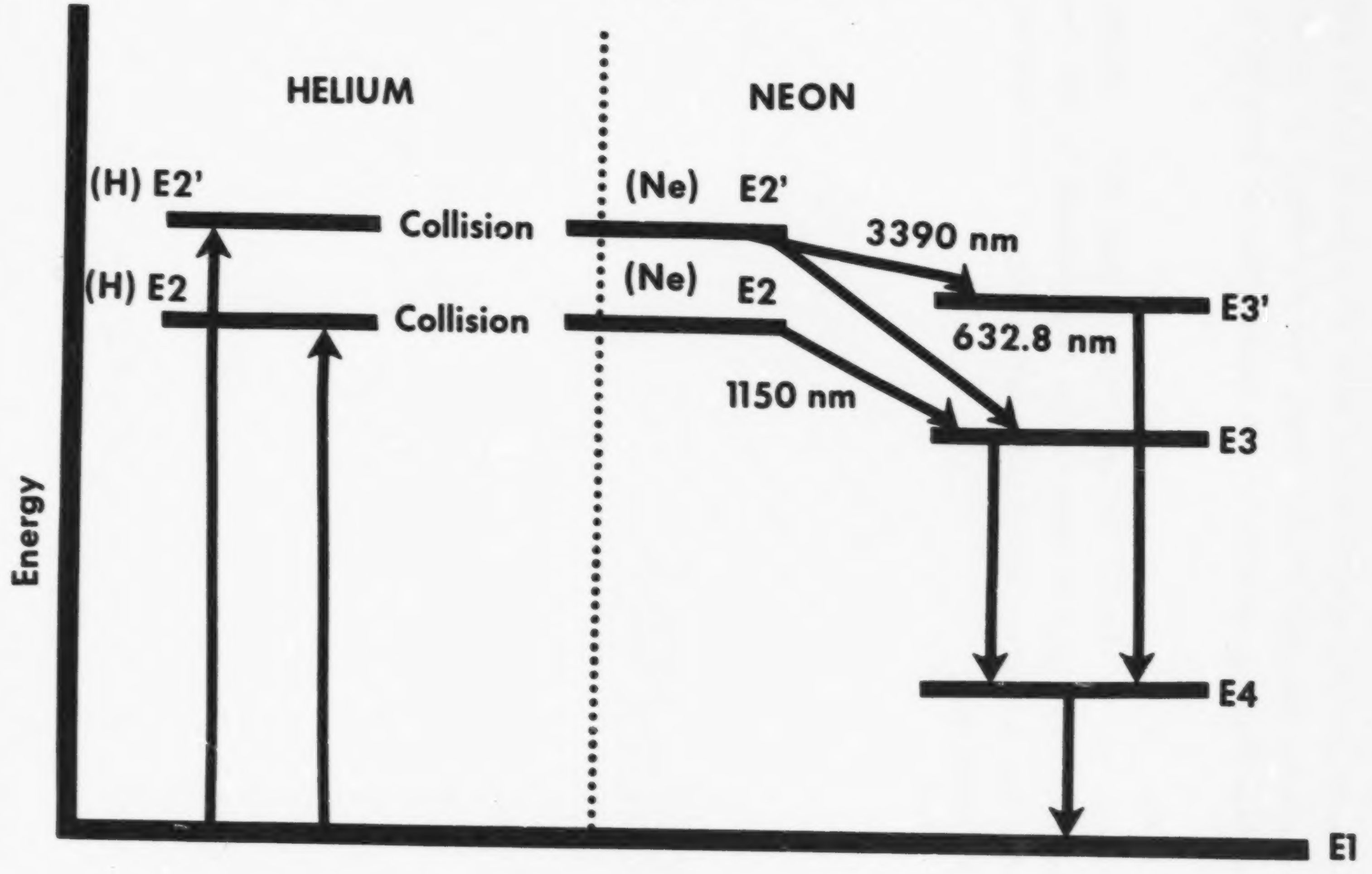
The He-Ne gas mixture is contained in a sealed tube. Excitation of the helium is accomplished by a discharge of electricity through the tube, similar to a neon sign. The mirrors may be enclosed within the tube or may form the end caps of the tube containing the He-Ne mixture. This is a rather solid geometrical configuration and results in a stable light output.

Figure 10


Energy
E1
E2
E3
E4
Photon Transition
Phonon Transition
Phonon Transition

ENERGY LEVELS OF NEON

Figure 11


HELIUM
NEON
Energy
(H) E2'
(H) E2
Collision
Collision
(Ne) E2'
(Ne) E2
3390 nm
632.8 nm
1150 nm
E3'
E3
E4
E1

ENERGY LEVELS OF GAS LASER (DETAIL)

Since the alignment of the mirrors is a delicate procedure, one common method is to mount the mirrors separate from the laser tube. When this is done, the ends of the laser tube are made of pyrex or quartz set at Brewster's angle to the axis of the laser, and the output is polarized light. (See Experiment 5, page 78 for an explanation of Brewster's angle.)

F. OTHER LASERS

Other lasers operate in similar but more complicated ways. Changes in molecular energy levels may be used rather than changes in electron energy levels, but output is still obtained through the stimulated emission of radiation.

PROPERTIES OF LASER LIGHT

The light output of a laser differs from the output of ordinary light sources. Four properties characterize the laser's output: small divergence, monochromaticity, coherence, and high intensity. These four properties are what make the laser so valuable and account for the ever-lengthening list of laser applications.

A. DIVERGENCE

When light emerges from the laser, it does not diverge (spread) very much at all. Thus the energy is not greatly dissipated as the beam travels. Laser beam divergence is measured in milliradians or 1×10^{-3} radians. There are 2π radians in a circle so one milliradian equals about 3 minutes of arc. A typical He-Ne laser has a rated divergence of 0.5 - 1.5 milliradians.

B. MONOCHROMATICITY

Laser light is very close to being monochromatic. The term "monochromatic" means one color, or one wavelength, of light. Actually, very few lasers produce only one wavelength of light. A typical He-Ne laser emits light at 632.8 nm, which is orange-red, and at 1,150 nm and 3,390 nm in the near and middle infrared regions. The He-Ne laser is usually designed to emit only one of the three wavelengths of light and the variation in this wavelength is slight.

C. COHERENCE

Coherence is a term used to describe particular relationships between two wave forms. Two waves with the same frequency, phase, amplitude, and direction are termed spatially coherent. For a fuller discussion of coherence, see Experiment 6, page 94.

No source of perfectly spatial coherent light is yet known; however, laser light comes so close that for most practical purposes it can be considered perfectly coherent. Sophisticated equipment is necessary to detect the variation from perfect spatial coherence.

D. HIGH INTENSITY

Laser light can be very intense. The sun emits about 7×10^3 W/cm^2/Sr/μm at its surface. Lasers are presently capable of producing more than 1×10^{10} W/cm^2/Sr/μm. (Sr = steradian) (It must be noted that a source of light that exceeds the sun in intensity may certainly be hazardous to vision.)

The magnitude 1×10^{10} W/cm^2/Sr/μm is somewhat misleading, for it represents only a single pulse of light. Energy is a measure of capacity for doing work and is usually classed as potential or kinetic energy. It is commonly measured in joules (J) in the metric system. Power is the rate at which work is being done and is measured in watts (W). The following relationships hold:

1 joule = 1 watt-second
1 watt = 1 joule/second

Thus, a laser capable of emitting 10 joules in one second can be termed a 10-watt laser. If those same 10 joules are emitted as a single pulse of 1/100th second duration, then the laser can be termed a 1,000-watt laser.

The output of pulsed lasers is usually indicated in terms of J/cm^2. The effect of the laser pulse is strongly dependent upon the amount of time it takes to deliver the pulse. Consequently, pulsed laser output is sometimes referred to in terms of $\frac{\text{J/cm}^2}{\text{sec}}$ or W/cm^2.

BIOLOGICAL EFFECTS OF LASER LIGHT

A. INTRODUCTION

Laser light can cause damage to living tissue. The extent of the damage depends primarily upon the frequency of the light, the power density of the beam, the exposure time, and the type of tissue struck by the beam. How does the laser light damage tissue?

B. DAMAGE MECHANISMS

Damage can occur through three mechanisms of interaction: (1) a thermal effect; (2) acoustic transients; or (3) other phenomena.[1] The latter two effects are only seen with high power density laser pulses.

When laser light impinges on tissue, the absorbed energy produces heat. The resultant rapid rise in temperature can easily denature the protein material of tissue, much as an egg white is coagulated when cooked. Since tissue is not homogenous, light absorption is not homogenous and the thermal stress is greatest around those portions of tissue that are the most efficient absorbers. Rapid and localized absorption produces high temperatures, steam, or results in explosive destruction of the absorber. Steam production, readily evident only at high exposure levels, can be quite dangerous if it occurs in an enclosed and completely filled volume such as the cranial cavity or the eye.

A second interaction mechanism is an elastic or acoustic transient or pressure wave. As the light pulse impinges on tissue, a portion of the energy is transduced to a mechanical compression wave (acoustic energy), and a sonic transient wave is built up. This sonic wave can rip and tear tissue and if near the surface, can send out a plume of debris from the impact.

Other phenomena such as free radical formation, are believed to exist during laser impact on biological systems, but this has not yet been conclusively demonstrated.

The laser is usually a hazard to only those tissues through which the light beam can penetrate and which will absorb the wavelength involved. With potential hazard evaluation and safety in mind, the concern is primarily with two organs -- the eye and the skin.

C. THE EYE HAZARD

Eye damage from light exposure has been recognized for over one hundred years. Czerny produced retinal burns in rabbits by using sunlight in the mid-1800's.[2] In 1916, solar eclipse burns on the retina of observers were described by Verhoff and Bell.[3]

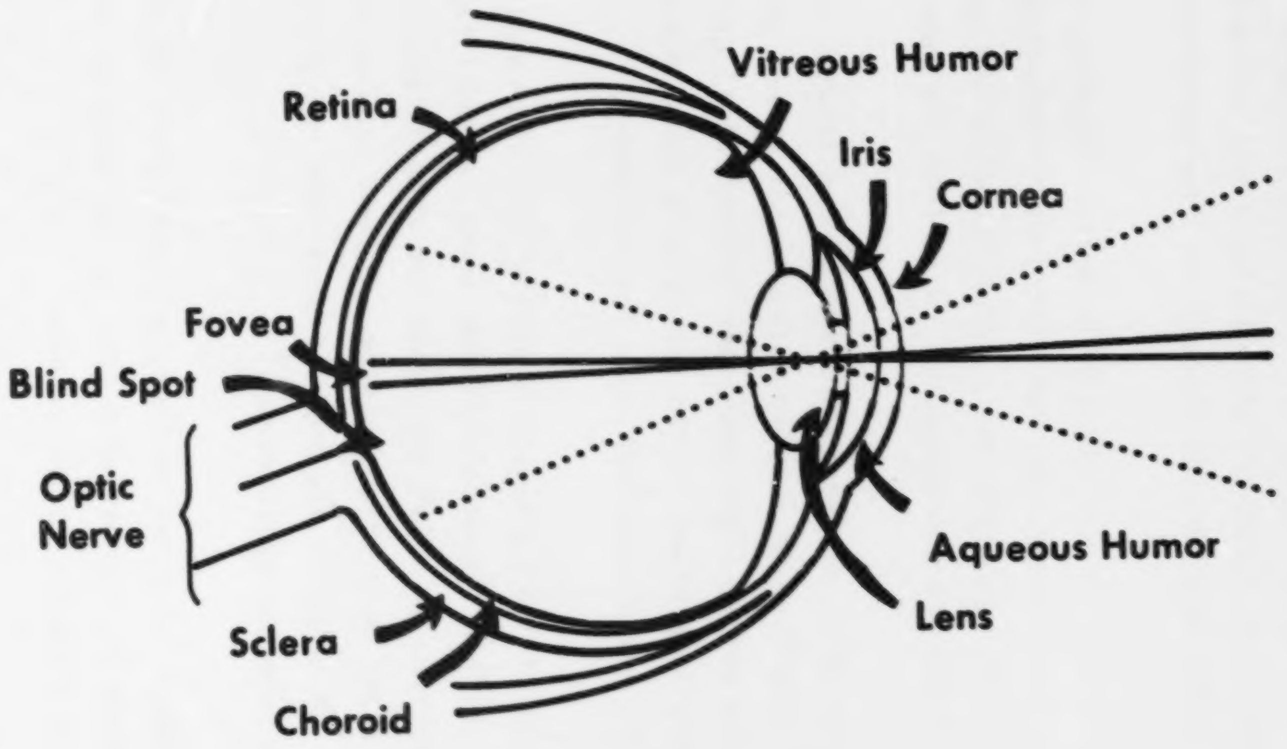
The hazard to the human eye posed by the use of lasers is obvious. A source of light energy that exceeds the sun in irradiance must surely be considered as a hazard to the eye. To better understand this, the anatomy of the eye will be considered. The cross-section of the human eye is illustrated in Figure 12.

The outer surface of the eye is a tough white tissue called the sclera. The anterior portion of the sclera is specialized into the cornea which is transparent to light. The cornea is the major focusing device of the eye.

Inside the eye are two fluid-filled cavities, both of which are under pressure to give structural rigidity to the eye. The anterior chamber contains a slightly viscous liquid, the aqueous humor. The rear chamber is filled with a very viscous, collagenous suspension, the vitreous humor.

Separating the two chambers is the lens which is attached by ciliary muscles to the sclera. These muscles alter the lens shape for fine focusing of the incoming light beam. Overlying the lens is the pigmented iris, a muscular structure designed to expand or contract and thus regulate the amount of light entering the eye.

Figure 12


Vitreous Humor
Retina
Iris
Cornea
Fovea
Blind Spot
Optic Nerve
Aqueous Humor
Lens
Sclera
Choroid

SCHEMATIC OF
HUMAN EYE

Lining the rear fluid filled chamber is the retina which contains the sensory cells for light perception. The retina itself is composed of tissue of two origins. The retinal tissue which the light encounters first is of neuro-ectodermal origin (about 150 μm thick) and contains the nerve cells for light perception. The underlying tissue is the pigment epithelium (about 10 μm thick) and contains great numbers of melanin granules. Its functions are to stop light reflection, absorb any scattered light, and provide support for the photoreceptor cells.

It is one of nature's quirks that light, before reaching the light sensor cells in the primate eye, must first pass through several membranes, nerve fibres, ganglion cells, bipolar cells and amacrone cells, and then must strike the photoreceptor cells from the rear.

The photoreceptor cells of the retina are of two types: rod and cones. Rods are quite sensitive to low light levels but cannot distinguish color. Cones are not as light sensitive but can distinguish color. The two types are intermixed in the retina with cones dominating near the center of the retina and rods near the periphery.

At the focal spot of the cornea-lens system lies the macula, an area of cones only. Within the macula is the fovea, a small region perhaps 250 to 300 μm across, in which the cones are densely packed. This is the center for clear or critical vision. To one side of the macula is a blind spot at which point the nerve fibres from the photoreceptors exit the eye to form the optic nerve.[4]

The retina subtends, in cross section, a visual angle of about 240°. It is loosely bound by connective tissue to the muscular choroid, which in turn is firmly attached to the sclera.[5]

Light is focused by the cornea and lens onto the fovea of the retina. In this process, the energy density of the light is concentrated by a factor of 10^4 to 10^6 over that falling on the pupil. For this reason, laser light may pose a serious hazard to the eye.

The human eye is relatively transparent to light in a wavelength range of about 400 to 1400 nm. This includes not only the visible range of 400 to 700 nm, but also a portion of the infrared which is not perceived. Figure 13 is a curve of optical transmission of light through the ocular media for both human and rabbit.[6] As can be seen, the greatest transmission occurs in the visible range.

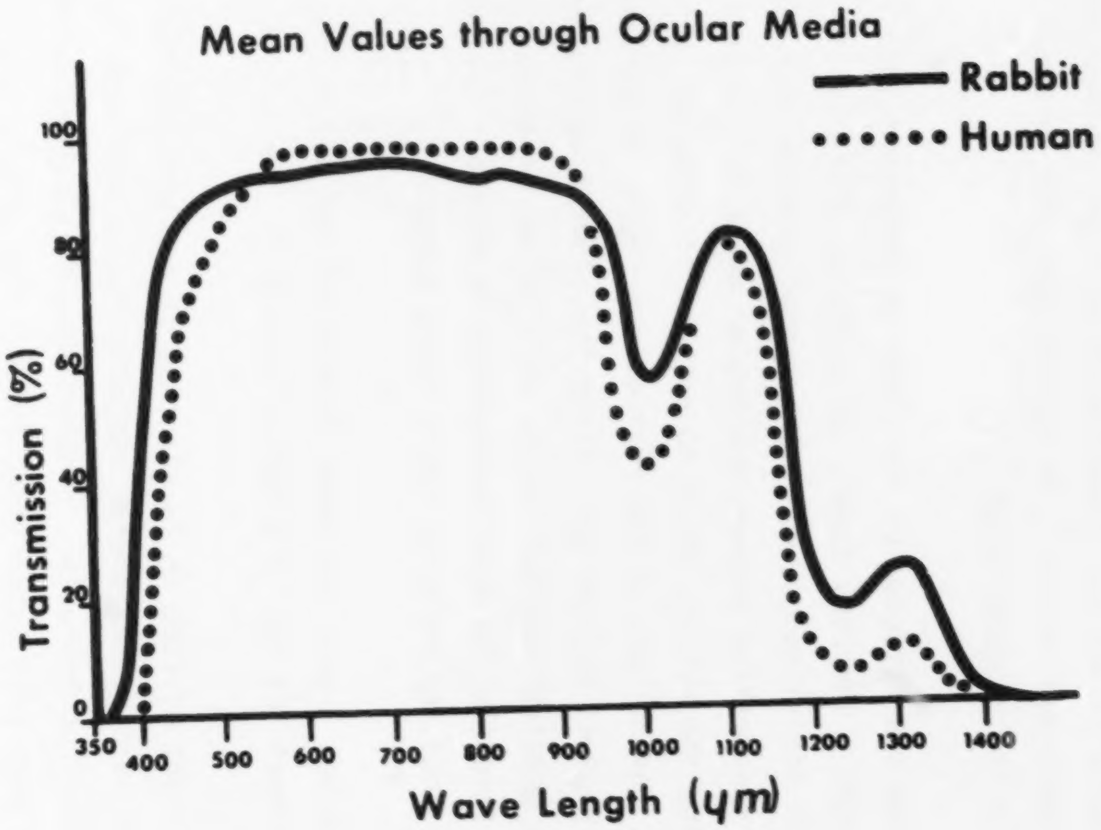
The portion of the eye affected by the laser is dependent upon the wavelength of the light. The ruby laser, for example, emits at 694.3 nm. From the curve of transmission, one can see that greater than 90 percent of the light is transmitted through the ocular media to the retina. Of the light reaching the retina, about 60 percent is absorbed in the neuroectodermal coat. Almost all of the rest of the light, 40 percent, is absorbed in the pigment epithelium. Since the pigment epithelium is only 10 μm thick, the greatest absorption per unit volume of energy occurs here,[7] and this layer is the most susceptible to damage. Lesions may be produced here without the receptor cells being damaged.

Helium-neon, krypton, argon, and xenon lasers all operate in the visible range, and all affect the eye in a manner similar to the ruby laser.

Neodymium laser light at 1060 nm is absorbed to a greater extent in the ocular media with less of its energy reaching the retina than in the case of visible light. Thus there is a greater chance of damage by means of steam production than from other laser types. The aqueous and vitreous bodies are colloidal suspensions in water, and the absorption characteristics of the media are similar to those of water.

Carbon dioxide lasers produce light at 10,600 nm. The eye is not very transparent to this frequency range and danger at low power densities comes from lesions produced on the cornea.

Figure 13



TRANSMISSION THROUGH OCULAR MEDIA

Research on eye damage has been under way for some time. The search for laser effects began shortly after the invention of the laser and is continuing. Most of the work has been aimed at determining the minimum amount of irradiation necessary to produce a visibly detectable retinal lesion from an acute exposure.

Current studies have been conducted with monkey, rabbit, and human eyes. The latter were eyes with some medical problems. Work is hampered by the fact that suitable human subjects are few and far between, and that the human eye is such a unique organ.

In truth, power density at the retina cannot be measured but must be calculated on the basis of transmission and focusing of the beam. The power density which can be measured is that on the cornea. On the basis of measurement at the cornea, lesions can be theoretically caused by as little as 10^{-6} J/cm^2 from a pulsed ruby laser.

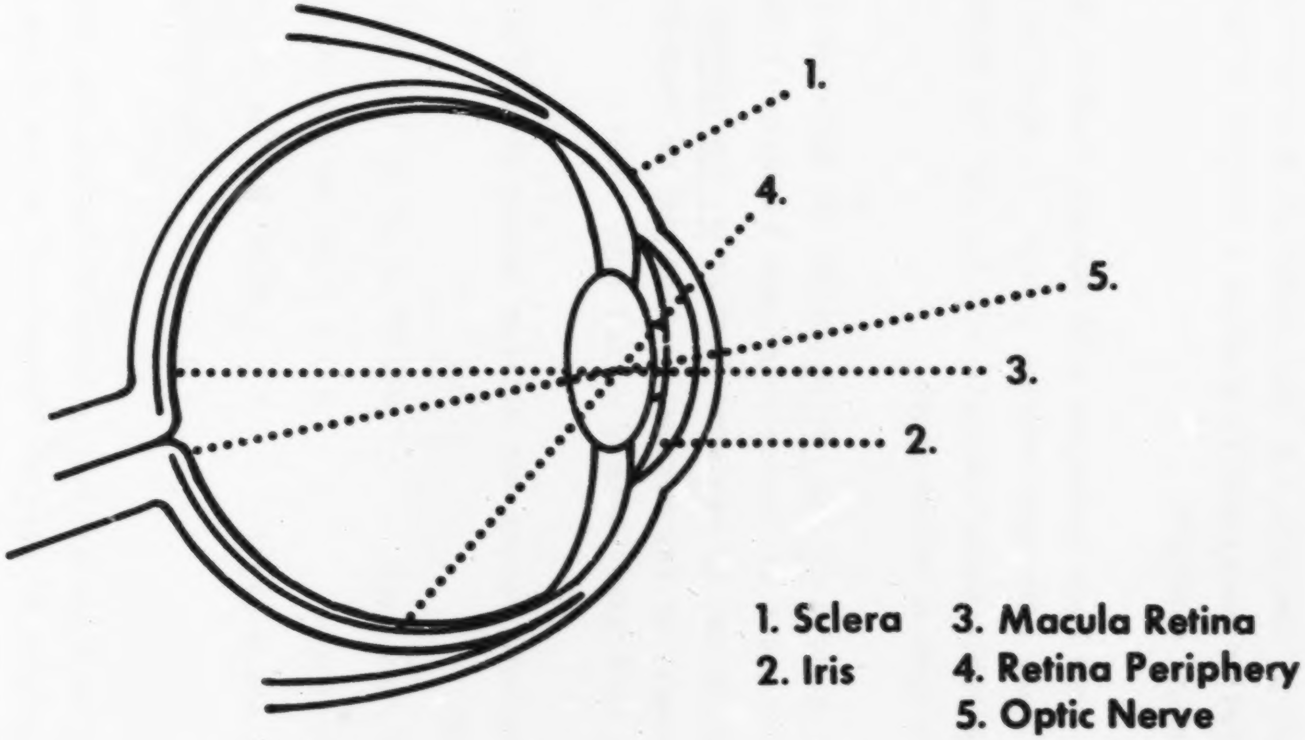
At present, threshold values for visible lesion production are approximately as follows:

Q-switched ruby laser	@ 0.07 J/cm^2 on the retina[8]
Pulsed ruby laser	@ 0.8 J/cm^2 on the retina[8]
Continuous white light	@ 6.0 W/cm^2 on the retina[8]
CO_2 laser	@ 0.2 W/cm^2 at the cornea[9]

Light levels below those producing visible lesions may also produce some permanent damage such as partial "bleaching" of the pigment for one particular light color. Work is now under way to detect such damage by histochemical means as well as by electroretinography.

Damage can result from laser impact on numerous eye structures. (See Figure 14). Oblique beam entrance may cause a lesion in the retina which goes unnoticed. A hit upon the optic nerve could result in complete

Figure 14


1.
4.
5.
3.
2.
1. Sclera
2. Iris
3. Macula Retina
4. Retina Periphery
5. Optic Nerve

POSSIBLE SITES OF LASER HIT ON EYE

destruction of vision. The iris is dark colored and quite susceptible, while the whole sclera can fall victim to high energy beams.

A special mention must be made of the CO_2 laser, whose infrared emission is destructive to the cornea. Corneal opacities are produced at a level of 0.2 W/cm^2 for 30 minutes continuous irradiation.[9] This is a rather high intensity as compared with other threshold levels, but then CO_2 lasers produce very intense beams and one is quite likely to encounter CO_2 lasers with continuous kilowatt outputs.

Maximum permissible exposure levels are calculated on a "Worst Case" analysis of the hazard. The laser beam is assumed to be aimed directly at the fovea, the iris is dilated to produce a large pupil diameter, and the eye is focused at infinity. Under these circumstances, maximum irradiation of the retina will occur.

D. THE SKIN HAZARD

The other area of concern besides the eye is the skin. Naturally, it is not as sensitive as is the eye, and if damaged, most injuries are more easily repaired. However, it too is subject to great damage from laser impact when energy densities approach several J/cm^2. Descriptions of skin damage are supplied for general interest and are probably not applicable in hazard considerations for He-Ne lasers.

The skin is not a homogeneous mixture. It is a specialized, layered structure with numerous odd inclusions, such as blood vessels and hair follicles. Like most other tissues, the skin is composed principally of water, and therefore the laser beams interact as if skin were sea water containing a number of inclusions. Consequently, the skin is relatively transparent to laser light.

Absorption of light in the skin occurs, for the most part, in the pigment granules and the blood vessels. The skin contains numerous pigments, the most common being melanin, which determine the color of one's skin. Visible laser light is selectively absorbed by the melanin granule, causing it to rise in temperature at a rapid rate, and causing cavitation around or bursting of the granule at high energy density exposure.[10]

Blood vessels are also quite susceptible to laser damage and are easily occluded or cauterized by a laser hit.

Under certain circumstances, the organ of concern is not the skin, but the underlying organs. Skin is so transparent that the visible light may pass through it to be absorbed by an internal organ. For example, the liver in mice is especially subject to this type of damage, lying close beneath the skin and being dark in color.

Laser damage to the skin ranges from a mild erythema to a surface charring, to a deep hole literally burned and blown into the skin. One rather sensational aspect is the plume, a kickback of debris present in high energy impacts. This plume may scatter tissue quite some distance from the point of impact.

LASER APPLICATIONS

A. INTRODUCTION

Soon after the invention of the laser, the device was described as "a solution looking for a problem". Since that time, however, a long list of problems in the areas of engineering and biology has been found for which the laser is providing eagerly-sought solutions. These solutions and their applications hold great promise for future work.

B. ENGINEERING APPLICATIONS

1. Communications

The higher the frequency of a carrier signal, the greater the amount of information that can be impressed upon the carrier. One optical carrier of He-Ne laser frequency (@ 5×10^{14} Hz) could in principle carry ten million simultaneous phone calls or eight thousand simultaneous television programs. This ability makes the laser very attractive to the communications industry.

Many problems await solution, however, before practical communications applications are possible. Modulation of the carrier beam has been accomplished, but it is a difficult process. Since the carrier is light, transmission from point to point can be stopped by such simple things as fog, rain, dust, or an object passing through the beam. The solution may be in transmission through pipes with mirrors directing the light around bends.

2. Tracking and Ranging Systems

A number of laser tracking and ranging systems are presently in use. This application is often referred to as LADAR (Laser Detection and Ranging), just as Radio Detection and Ranging is referred to as RADAR.

Ranging systems record the time for a signal to travel to the target and return and translates this time to distance. The small divergence of the beam is important because it allows the operator to pinpoint the object for which readings are taken. The Army has developed a rangefinder which utilizes this concept.

3. Surveying

The collimated beam of the laser is ideal for a number of surveying applications. One laser, operating continuously, can replace two men and a transit.

Giant earth-boring machines are now aligned through use of the laser. Bulldozers clearing land, graders leveling land, barges or dredges working on dredging harbors or setting piers, pipe layers and ditch diggers are all making use of the laser as a simple method of alignment.

4. Mechanical Measurements

The Michaelson interferometer has been the center of renewed interest since the advent of the laser. Formerly, the interferometer could be used only to measure very small changes in length. Now the device is useful for distances up to several hundred feet.

Applications include the following: seismology, where a stable source of coherent light can detect very small earth movements; metalworking, which utilizes the interferometer to control the operations of a milling machine; flow rate control; and large scale movements such as building sway or bridge movements.

5. Welding and Cutting

The high intensity output capability of the laser was first demonstrated by burning holes in razor blades. Presently this capability is being utilized on production lines in cutting and welding applications.

Diamonds are used as dies to make wire. Before the discovery of the laser, drilling holes in the diamonds took days. Today, the use of lasers has reduced the cutting time to minutes. Cutting and working of other hard materials is also done easily with the laser.

Welding of wires in transistors and microchip circuits is also done using lasers, and laser beams can be projected through the envelope of a glass tube to weld broken wires inside.

6. Holography

The laser's coherent light has given new impetus to the photographic process of holography. Three-dimensional images are being used for display devices and as a method of spotting defects in automobile tires, as well as in scientific research applications such as particle size measurement. Recently, a cube of crystal material has been used to record numerous holograms. The small size of the cube and the large number of three-dimensional images stored may herald a new era in information and data storage and retrieval.

C. BIOLOGICAL APPLICATIONS

I. Retinal Coagulation

The retina of the eye is loosely attached to the choroid coat. The retina is of neurodermal origin while the choroid is ectodermal. In the embryo, these two join and subsequently throughout the life of the individual are held by a thin layer of connective tissue. In the adult, any number of circumstances, including trauma, can result in the separation of the retina from the body of the eye. This of course leads to a loss of vision because the light cannot be properly focused upon the detached retina.

For a number of years, retinas were reattached by using a long needle-like probe to weld the retina to the choroid with a scar.[11] This worked quite well, producing one or more blind spots but allowing the proper focus to be attained once more. About 1950, the xenon photocoagulator was introduced, producing this same effect by means of a pulse of intense white light which, when focused by the lens on the retina, resulted in reattachment by coagulated blood in a fashion similar to a spot weld.

More recently, retinal repair has been accomplished by using a laser as the light source. Ruby lasers were used first, then neodymium, and finally argon lasers. The real value of using the argon laser over the xenon photocoagulator is the size of the spot weld. An argon laser can produce welds much smaller than the size of a xenon weld, allowing finer "stitching," this being of particular value around the fovea. In addition, neither anesthesia nor hospitalization is required with laser photocoagulation.

2. Skin - Cosmetic Repair

Much use has been made of the laser's destructive effects in treating skin disorders. Since the laser light is preferentially absorbed by pigmented tissue, one of the first experiments undertaken was the removal of tattoos. Favorable results were obtained, leading to further work, especially in the cosmetic treatment of angiomas.

An angioma is an excessive proliferation of blood and lymph vessels in the upper skin layers. The multitude of fine blood vessels in the upper skin layers produce a discoloration of the skin and appears as a port wine color. The impact of a laser can occlude the blood vessels and blanch the skin, leading to an eventual healing of the impact area and normal coloration of the skin.

3. Skin Cancer

Skin cancers have also been experimentally treated. Since there is a difference between normal and cancerous skin cells, a search has been under way for a dye or pigment that is completely selective for cancer cells. Partial results have been obtained and cancer cells can now be stained considerably darker than normal cells. The darker cancer cells are then more susceptible to the impact of a laser beam because they absorb more light energy and are more severely damaged than are normal unstained cells.

Two problems have arisen with this treatment. First, the plume of debris from the laser impact was found to contain viable cancer cells, posing a possible hazard to operating room personnel. Second, the impact drove some of the tumor cells deeper into uninfiltrated tissue, thus spreading the cancer. The first problem has been solved by placing a cone over the laser head which catches the plume from the impact. This cone may even be attached to a suction device for vacuum cleaner action. The second problem may be overcome by improved techniques.

Two types of cancer treatment have been practiced. A low energy beam has been used to selectively disrupt tumor cells. Higher energy beams are used to excise nodules from deeper tissues.

4. Bloodless Surgery

The possibility of bloodless surgery with a laser scalpel has given rise to many new techniques in surgery. It facilitates surgical procedure on organs such as the liver and kidney where blood loss is a problem. High energy argon lasers should soon become a tool for liver operations, with concurrent use of plastic adhesives to complete closure.

5. Transillumination

Transillumination is a technique whereby a strong light is projected through soft tissues to aid in detecting tumors. The skin is relatively transparent to light, as is demonstrated by putting your thumb over a flashlight. Lasers hold promise for this type of examination allowing, for example, an immediate examination for breast cancer without the potential hazard or wait associated with x rays.

6. Neurosurgery

Neurosurgery appears to be a promising area for laser use. Precisely controlled cutting is extremely important and can be accomplished with lasers. Transection and tumor treatment will benefit from the use of lasers, and bloodless tumor removal may be within reach. A number of operations may be done in the grey matter using the laser, thus lowering the possibility of infection.

7. Dentistry

Some experimental work has already been done in the field of dentistry. The glazing of teeth by a laser has been shown to reduce significantly the demineralization of enamel, and may also be effective against caries. Dental caries have been exposed to laser impact with favorable results. If the caries can be retarded or stopped by laser impact, dentistry will have gained a valuable tool.

8. Cell Identification

A new method of instant and positive identification of micro-organisms and tissues is now being produced commercially. The sample in question is cooled to a low temperature and irradiated with ultraviolet laser light. Under those circumstances the sample itself produces phosphorescent light whose frequency and decay time are unique for the organism. A small computer matches the frequency and decay time data with information previously stored and can identify instantly the present of specific micro-organisms or tissues.

SAFETY IN CLASSROOM LASER USE

A. INTRODUCTION

Laser light poses a definite hazard to the eye and, to a lesser extent, the skin. The purpose of this manual is to assist you as an instructor in evaluating the hazard involved in classroom laser use and to suggest precautions that may be taken to reduce this hazard.

The U.S. Public Health Service has not, at this time of writing, established radiation protection guides for laser irradiation. However, a number of private corporations, laboratories, and military and government groups have formulated internal standards for safe laser use. One can use these formulations in evaluating one's own criteria for laser safety. (See reference list, page 116).

One note of warning must be made regarding the use of these published guides. Most of the guides were compiled from work performed in the determination of the damage threshold for visible eye lesions. Because of the importance of these lesions to sight, the term "threshold" must be carefully scrutinized. Just what is the lowest level of biological change one should use as the criterion for damage? No general agreement now exists.

Visible lesions may not be true threshold lesions because more sensitive processes may detect permanent damage at exposure levels well below those producing visible lesions. Histochemical methods can be used to detect permanent enzyme inactivation at exposure levels 10-15 percent below those resulting in visible lesion production. Electroretinography can be used to detect some permanent changes at exposure levels 50 percent below visible lesion levels. Permanent damage may result at even lower levels.

B. HAZARD CALCULATIONS

Exposure standards are of little value unless used. Proper use of exposure standards includes an estimate of the hazard presented by the beam from your laser. Let us take a brief look at how to determine what hazards exist.

An accurate determination of the hazards posed by a laser requires measurement of several beam parameters. Many methods for measuring or defining the beam parameters are presently in common use, all requiring the use of calibrated and costly electronic gear. However, an approximate idea of the hazard posed by a laser can be gained by using the manufacturer's specifications.

One note of caution: The specifications listed by a laser manufacturer are likely to be minimal guaranteed levels for a particular model, and an individual laser may exceed these specifications. A nominal two milliwatt laser will usually have an actual output greater than 2 mW. A laser with a nominal divergence of 1.0 milliradians may have a divergence of 0.8 milliradians. These supplied figures can provide a general idea of the power densities involved. However, it must be realized that this can lead to a serious underestimation of the hazards involved. Use of the nominal specifications to calculate the power density leads to a nominal calculated value which may be considerably less than that determined by direct measurement.

Exposure levels which are listed as "safe" or "tolerable" are given in units of irradiance, mW/cm^2. Therefore, the output of your laser must be expressed in similar units. The usual information given by a laser manufacturer, and typical values for a classroom type He-Ne laser are given below:

Power output	1.0 milliwatts
Beam diameter at aperture	1.5 millimeters
Beam divergence	1.0 milliradian

The irradiance at the aperture is given by the following formula:[12]

$$P_a = \frac{P}{\text{area}} = \frac{P}{\pi(D_a/2)^2}$$

where:

P_a = irradiance at aperture

P = power output

D_a = Beam diameter at aperture in cm

For the laser listed above

$$P_a = \frac{1.0 \text{ mW}}{3.14\ (0.15 \text{ cm}/2)^2}$$

$$= 57.1 \text{ mW/cm}^2$$

$$= 5.7 \times 10^{-2} \text{ W/cm}^2$$

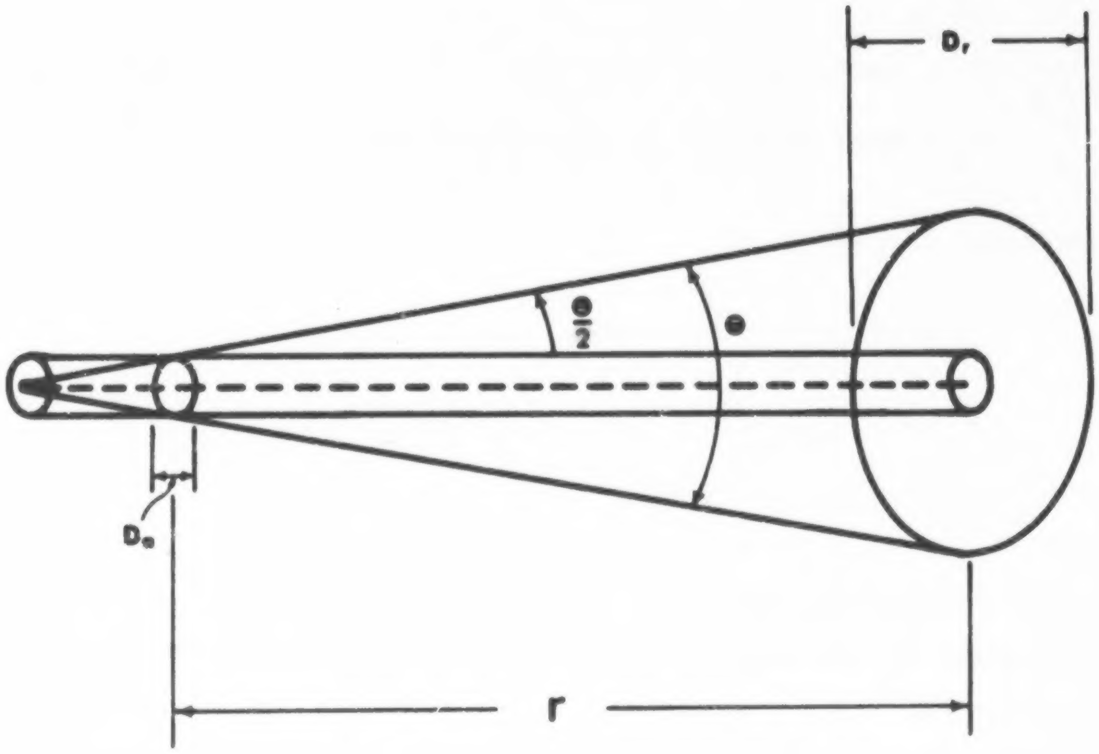
This laser, therefore, has an output irradiance of approximately 6×10^{-2} W/cm^2 at the aperture. If we compare this with the "safe" value of 5×10^{-5} W/cm^2 recommended by the American Conference on Government Industrial Hygienists (1968) for daylight illumination,[8] it is approximately 1000 greater than the "safe" value.

As the laser beam travels beyond the aperture, it diverges slightly. At a distance of r meters, the beam will have diverged to a diameter D_r. This is illustrated in Figure 15.

The formula for determining the irradiance at a distance r centimeters from the aperture is:

$$P_r = \frac{P}{\pi(D_r/2)^2} = \frac{4P}{\pi(D_r)^2}$$

Figure 15



D_r
$\frac{\theta}{2}$
θ
D_o
r

BEAM DIVERGENCE

where:

P_r = irradiance at distance r

D_r = diameter of beam at distance r in centimeters

The divergence of the beam in radians can be used to determine the beam diameter at distance r as follows:

$$D_r \approx r\phi + D_a$$

where:

r = distance in centimeters

ϕ = divergence in radians

D_a = aperture diameter in centimers

The irradiance can thus be determined at any point. Calculate, for example, the irradiance at a distance of about 40 feet or 13 meters (a reasonable distance from the front to the rear of a classroom.

$$\begin{aligned} D_r &= (1300 \text{ cm} \times 1.0 \times 10^{-3} \text{ radians}) + (0.15 \text{ cm}) \\ &= (1.30 \text{ cm}) + (0.15 \text{ cm}) \\ &= 1.45 \text{ cm} \end{aligned}$$

$$\begin{aligned} P_r &= \frac{4(1.0 \text{ mW})}{3.14(1.45 \text{ cm})^2} \\ &= \frac{4 \times 10^{-3} \text{ W}}{6.6 \text{ cm}^2} \\ &= 6.06 \times 10^{-4} \text{ W/cm}^2 \end{aligned}$$

As can be seen, even a small classroom type laser can emit enough power to be unsafe for direct viewing of either the primary beam or of specular reflection (see Experiment 3, page 64), even though the viewer may be seated in the rear of a classroom.

C. SAFETY AIDS

The laser can be used safely in the classroom. Common sense and preplanning of experiments will point out the most obvious hazards. Safety aids will prevent injury even when the unexpected does occur. Let us look at some useful aids for classroom use.

1. The Beam Shutter

Lasers are constructed to withstand continuous use for 8 hours a day, 5 days a week. Their life span is actually shortened by intermittent use. Turning the laser on and off at short intervals is also inconvenient. One way to overcome this strain and inconvenience is by the use of a beam shutter.

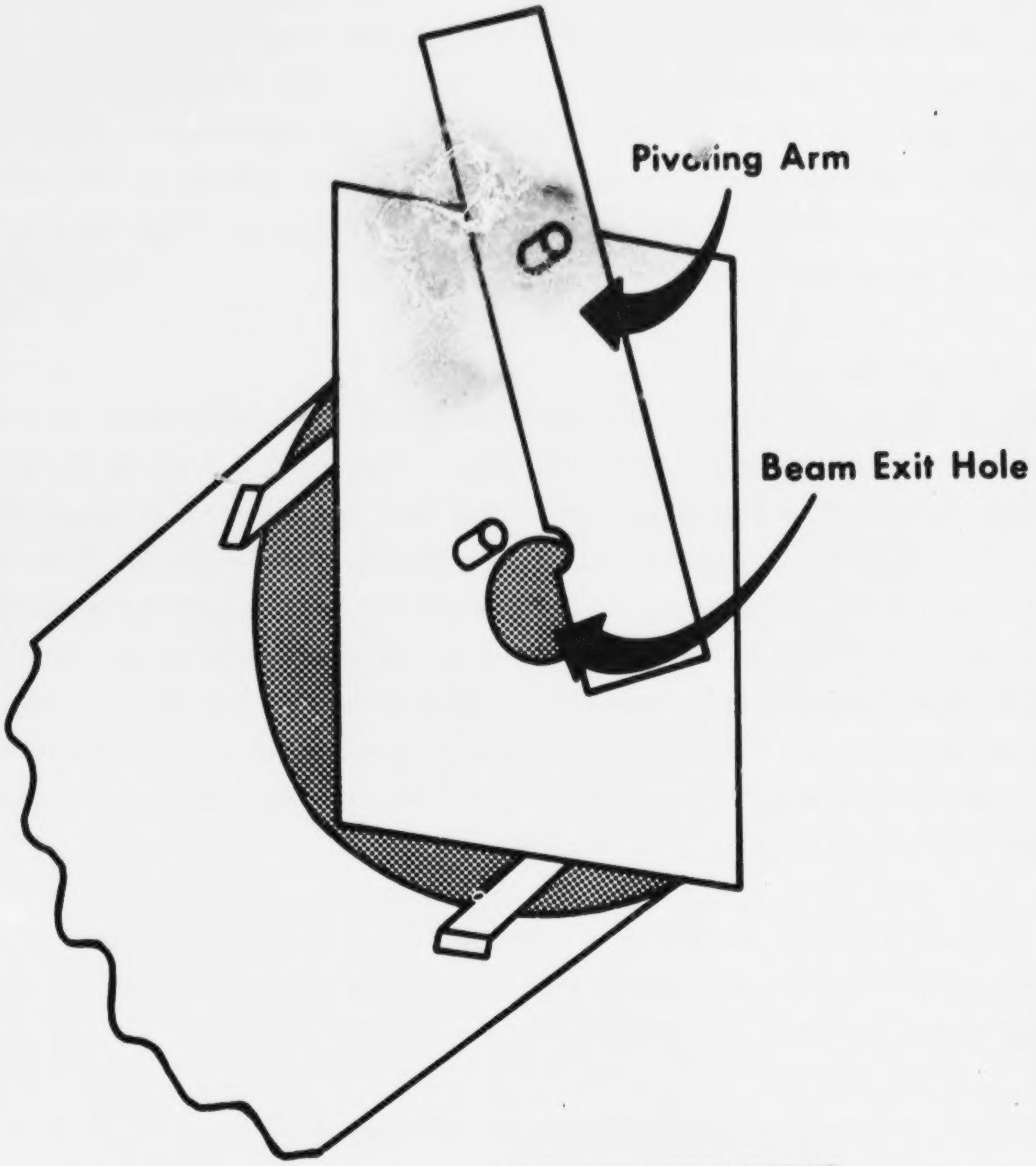
The shutter can be a simple mechanical device fitted over the aperture of the laser. It allows the operator to cut off the laser beam without actually turning off the laser. The shutter should be made of black, non-reflective material and should completely stop passage of the laser beam. One example is shown in Figure 16.

Use of the beam shutter can reduce the hazard to the operator whenever the experimental configuration in front of the laser is being changed or altered. It eliminates the possibility of accidental reflection from a piece of equipment during the changing process. As with all safety aids, one must develop the habit of shuttering the beam at ALL times it is not actually needed.

2. The Target

The laser beam will travel outward from the laser until absorbed or reflected. To prevent accidents a target of suitable material should be provided for the beam. This target should be made of a non-reflective material and should also be large enough to stop the beam under a wide variety of experimental situations. Black foam rubber material is one example of a good beam target. Black ink on blotter paper also makes a good target.

Figure 16


Pivoting Arm
Beam Exit Hole

BEAM SHUTTER

3. The Demonstration Box

Accidents can happen during setup and alignment of the laser demonstration. Observers should be protected during this phase of the demonstration by placing a shield between the laser and the observers. One way of doing this is to hang a black, dull-surfaced curtain or drape between the observers and the demonstration. Another simple and inexpensive way of accomplishing this task is to use a large cardboard box with holes in either end for entrance and, if necessary, exit of the laser beam. Large panels can be cut out of either side, one for use while setting up the experiment, another for viewing. Doors or flaps can cover the openings when not in use. An example is shown in Figure 17.

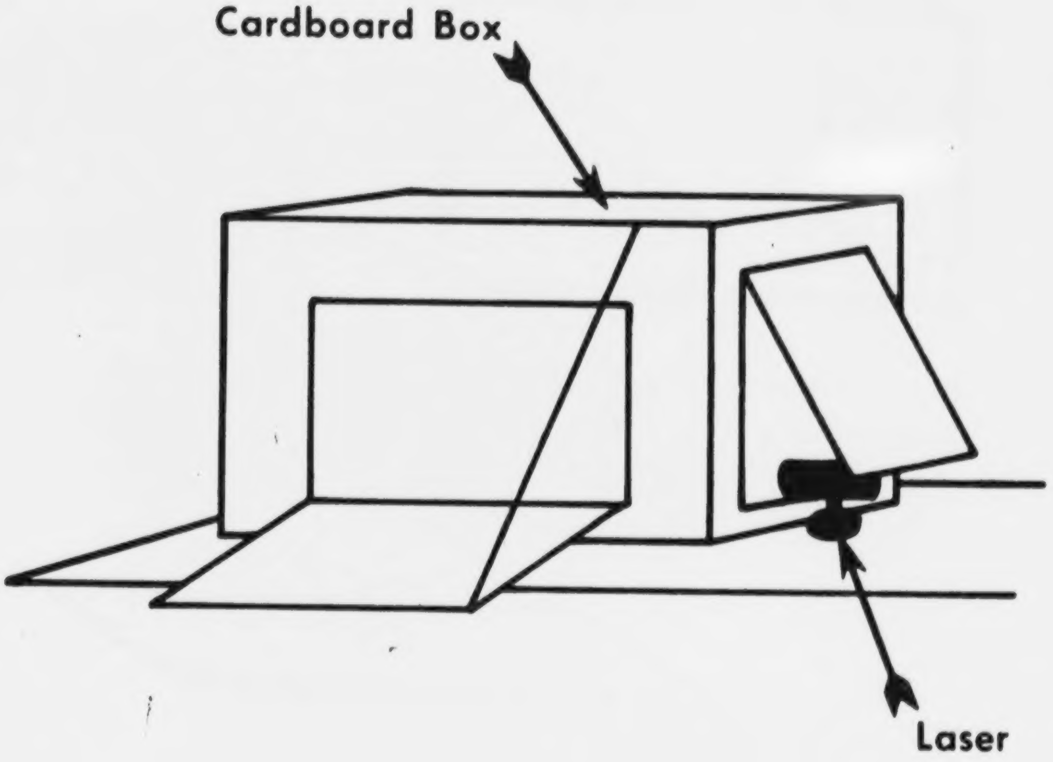
4. The Display Tank

Laser light is invisible from the side unless it is scattered by a medium. One convenient and relatively safe way of viewing the beam is to use a clear, liquid-filled display tank. The tank can be readily constructed out of plexiglass or any clear, thick plastic. Surfaces should be flat and square with one another to allow accurate passage of the beam through the tank. The liquid filling can be made of a solution of a clear substance with some large molecules. Transmission oil may be acceptable, or a soap solution with some red food coloring mixed in. (See Figure 18). Caution must be exercised in setting up the display tank, as reflections from the tank sides could be hazardous.

Do not use a jar or bottle as a display tank. Inexact alignment of the beam could result in the beam being specularly reflected from the round side of the bottle.

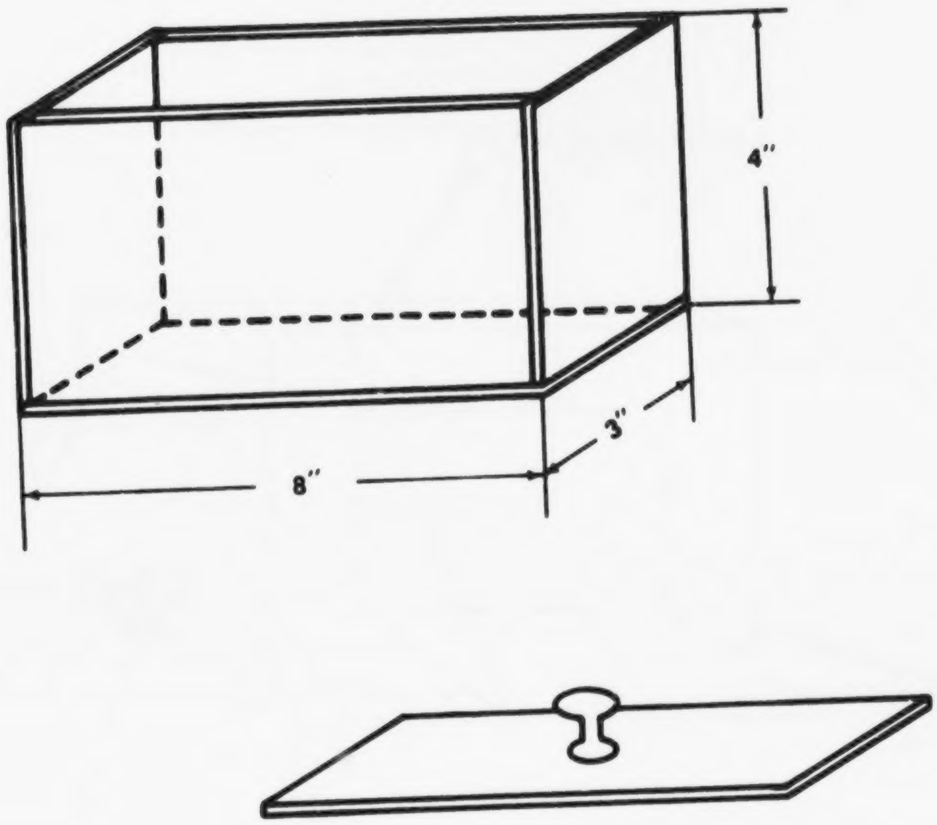
A second, and perhaps more convenient, display device can be made from plastic casting resin such as is found in hobby stores. When cast into a square or rectangular block, with one face painted flat black, the resin will serve well to display a beam passing through it.

Figure 17


Cardboard Box
Laser

DEMONSTRATION BOX

Figure 18



DISPLAY TANK

5. Black Paint

Painting the surfaces of demonstration equipment with a flat, dull, black paint may be the most important single precaution one can take. It is unfortunate that many pieces of optical gear are supplied with bright plated surfaces. Chrome and stainless steel are beautiful, but the specular reflection from these surfaces can be literally blinding.

6. Reduction of Beam Power Intensity

Many lasers available for educational use furnish far MORE light than is needed to conduct a demonstration adequately. The power density of the beam should be reduced to a level commensurate with the level of light actually required. This reduces the potential for accidental eye damage. Two methods work well. The first is the simple expedient of inserting an absorbing filter in the path of the beam. This filter may be a neutral density type. Any other material which effectively absorbs the light while at the same time does not scatter the beam, will also serve. The second method is to increase the diameter of the beam by means of a pair of lenses. The first lens should spread the beam to an overall diameter of approximately one centimeter. The second lens is then used to recollimate the beam to near its original divergence. Expanding the beam decreases the power density and lessens the hazard posed by direct or indirect viewing of the beam. If possible, permanent attachment of the lenses to the laser is recommended. It should be noted that expanding the beam will not destroy the coherent properties of laser light. (Figure 19).

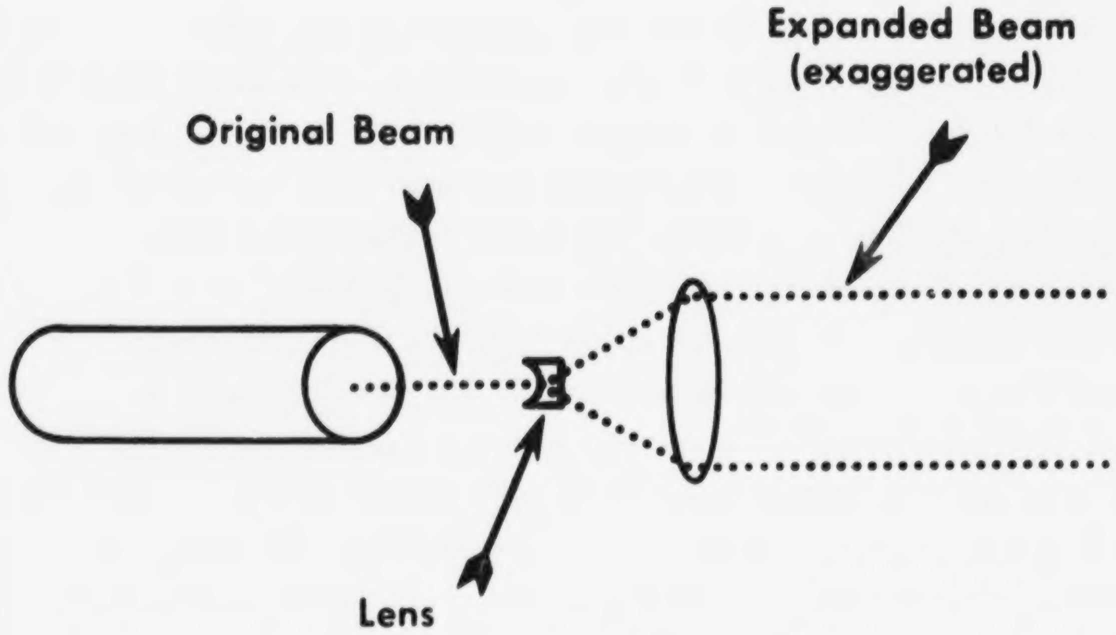
7. Key Lock

If possible, the classroom laser should be purchased with or have installed a key lock for the power supply. When so constructed, the unauthorized use of the laser can be readily prevented by the instructor.

8. The Dry Run

All experiments should be dry-run before presenting them to a class. This allows the operator to ascertain where the hazards are or may be and lets him eliminate them before they can cause damage.

Figure 19


Expanded Beam
(exaggerated)
Original Beam
Lens

BEAM EXPANDER

D. GENERAL SAFETY RULES

Overexposure of the eye and skin are of primary concern in laser work, but other hazards also exist: (1) electrical shock; (2) toxic chemicals; (3) exploding components, such as flash tubes or optics; (4) cryogens for cooling; and (5) noise or bright flash levels which may startle personnel and thereby cause an accident. Items 2, 3, 4 and 5 are not usually associated with He-Ne lasers.

The best safety rule is to know that a potential hazard exists with any laser and to combine this knowledge with good common sense. A listing of some general rules is given below. These guides should be followed whenever the laser is used in either a classroom or a laboratory.

1. Work Area Controls

   a. The laser should be used away from areas where the uninformed and curious would be attracted by its operation.

   b. The illumination in the area should be as bright as possible in order to constrict the pupils of the observers.

   c. The laser should be set up so that the beam path is not at normal eye level, i.e., so it is below 3 feet or above 6-1/2 feet.

   d. Shields should be used to prevent both strong reflections and the direct beam from going beyond the area needed for the demonstration or experiment.

   e. The target of the beam should be a diffuse, absorbing material to prevent reflection.

   f. Remove all watches and rings before changing or altering the experimental setup. Shiny jewelry could cause hazardous reflection.

   g. All exposed wiring and glass on the laser should be covered with a shield to prevent shock and contain any explosions of the laser materials. All non-energized parts of the equipment should be grounded.

h. Signs indicating the laser is in operation and that it may be hazardous should be placed in conspicuous locations both inside and outside the work area and on doors giving access to the area.

i. Whenever possible, the door(s) should be locked to keep out unwanted onlookers during laser use.

j. The laser should never be left unattended.

k. Good housekeeping should be practiced to insure that no device, tool, or other reflective material is left in the path of the beam.

l. A detailed operating procedure should be outlined beforehand for use during laser operation.

m. Whenever a laser is operated outside the visible range (such as a CO_2 laser), some warning device must be installed to indicate its operation.

n. A key switch to lock the high voltage supply should be installed.

2. Personnel Control.

   a. Avoid looking into the primary beam at all times.

   b. Do not aim the laser with the eye: direct reflection could cause eye damage.

   c. Do not look at reflections of the beam: these too could cause retinal burns.

   d. Avoid looking at the pump source at all times.

   e. Clear all personnel from the anticipated path of the beam.

   f. Do not depend on sunglasses to protect the eyes. If laser safety goggles are used, be certain they are designed to be used with the laser being used.

   g. Report any afterimage to a doctor, preferably an ophthalmologist who has had experience with retinal burns, as damage may have occurred.

h. Be very cautious around lasers which operate in invisible light frequencies.

i. Before operation, warn all personnel and visitors of the potential hazard. Remind them that they have only one set of eyes.

EXPERIMENT SECTION

The following experiments are provided to assist the instructor in demonstrating properties of light and other electromagnetic radiation using the laser. The instructor is expected to be familiar with the classical elementary theory of light; therefore, explanations will be kept to a minimum. The experiments are so designed as to produce an effective demonstration with minimum equipment and maximum safety.

Equipment necessary for these demonstrations:

1. Laser
2. Display tank
3. Support for display tank
4. Milk
5. Aerosol room deodorizer or smoke source
6. Liquid detergent
7. Ink
8. Boiled or distilled water
9. Detector (CdS light meter with red filter)* see note below
10. Mirror
11. Pivot mount for mirror
12. Protractor
13. Ruler
14. Thick slab of glass
15. Prism (45° - 45° - 90°)
16. Polarizing filters (3)
17. Small test tubes
18. Quarter wave plates (2) doubly refracting, red
19. $AgNO_3$
20. Single-slit diffraction aperture
21. Double-slit diffraction aperture
22. Circular diffraction aperture
23. Divergent lens

24. Hologram
25. White paper
26. Transmission grating
27. Razor blades

NOTE: Light detection and intensity measurement can be accomplished by use of a photographic light meter, preferably employing a CdS detector. The light levels from a 2.5 milliwatt laser will not overdrive the meter and used meters can be purchased in camera stores. The meter's response to light is not linear, however, and response must be calibrated against a more accurate standard.

EXPERIMENT I -- SCATTERING OF LIGHT

Explanation:
When light passes through the atmosphere, it is scattered by the large number of gas molecules and particles that make up the atmosphere. Objects are visible only because of the light they scatter toward the viewers' eyes. It is for this reason (i.e., the lack of light scattered toward them) that astronauts are largely in the dark when they travel in orbit beyond the earth's atmosphere. For this same reason, an observer may not see a laser beam headed across his path. On the other hand, if smoke is blown into the path of a laser beam, it immediately becomes visible.

This mechanism of optical scattering varies with the size of the scattering particles. Particles such as smoke may be considered "large" if their radii approach the wavelength of the incident light. The scattering from such particles is referred to as large particle (i.e., Mie) scattering. In this type of scattering the particles may be considered as opaque spheres which scatter according to the principles of the diffraction theory. It is this type of scattering that can pose a potential hazard when high-powered lasers are used in the atmosphere.

Particles whose radii are much smaller than the wavelength of the incident light (radius $< .05\ \lambda$), scatter by a different mechanism called Rayleigh scattering. In this type of scattering, each microscopic particle acts as an electric dipole, reradiating the incident wave by electrically coupling into resonance with the electric field of the incident light. This type of scattering can be seen by observing different regions of the daylight sky through a polarizing filter. An experiment using $AgNO_3$, a solution which exhibits Rayleigh scattering, is given in the section on polarization (Experiment 4, part B).

Materials:

Laser
Display tank
Boiled or distilled water
Milk
Smoke source or aerosol can

EXPERIMENTAL PROCEDURE

Large Particle or Diffraction Scattering

Direct the laser beam so that it passes through the clean display tank filled with boiled or distilled water. The path of the beam will probably not be visible in the water. Add a small amount of homogenized milk to make the water turbid. The path will then become visible. Instead of milk, a concentrated solution of colloidal silica solution can be added to the water to make a permanent display solution. Large particle scattering can also be demonstrated by blowing smoke or the spray from an aerosol can into the path of the laser beam.

EXPERIMENT 2 -- ABSORPTION OF LIGHT

Explanation:

In passing through a material, laser light, like all electromagnetic radiation, undergoes absorption which can be expressed by the exponential relationship $I = I_o e^{-\mu x}$, where μ is a function of the absorbing material and the wavelength of the light, and x is the thickness of the absorbing material. If a green piece of cellophane is placed in the path of a helium-neon laser beam (i.e. red light), there is a substantial reduction in the beam intensity. If, on the other hand, a red piece of cellophane is used with the same beam, relatively little absorption occurs. This principle of selective absorption of light from laser beams with given wavelengths is used in some of the commercially available protective goggles sold for use with lasers. The experiment here will demonstrate both quantitatively and qualitatively how the absorption of light depends upon the thickness of the absorber.

Materials:

- Laser
- Display tank
- Liquid detergent
- Detector for measuring light intensity
- Ink

EXPERIMENTAL PROCEDURE

Prepare a display solution by adding a few drops of a liquid detergent in water and stir until it is uniformly mixed. Fill the display tank with this solution and project the laser beam into the tank so that the path of the beam is clearly visible. Now add a drop or two of blue or black ink to the solution and stir until the solution is uniform. Notice that this causes the beam intensity to decrease rapidly as it penetrates further into the solution. Continue to stir in ink a drop at a time until the beam vanishes (i.e. is completely absorbed) before it reaches the opposite end of the tank.

To obtain a quantitative measurement of the exponential absorption of light in a material, direct the laser beam onto a detector which measures light intensity or beam power. Record this value. Using various pieces of absorbing materials such as a semi-opaque plastic, insert one thickness at a time so as to gradually increase the thickness of the material through which the laser beam passes. Record the light intensity for each value of the total thickness of the material and plot the data on semi-log paper. What is the shape of the line obtained? Why?

EXPERIMENT 3 -- REFLECTION OF LIGHT

Explanation:

Light and the manner in which it is reflected are of prime importance in geometrical optics. There are two types of reflection: (1) diffuse reflection, in which light striking a rough surface is randomly scattered in many directions, and (2) specular (i.e. mirror-like) reflection, in which the incident light is reflected from a smooth surface in accordance with the law of reflection (i.e., the angle of incidence equals the angle of reflection, as shown in Figure 20). As discussed in most physics texts, the behavior of light at an interface between two media is governed by both the law of reflection and the law of refraction.

Materials:

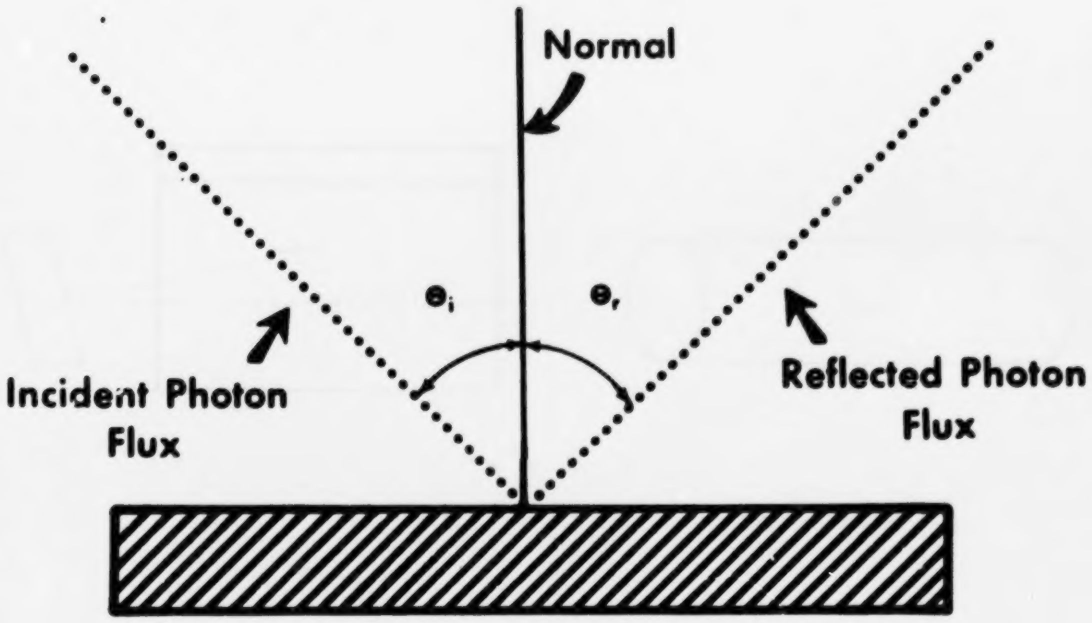
- Laser
- Display tank and display fluid
- Support for tank
- Mirror on pivot mount
- White paper
- Protractor

EXPERIMENTAL PROCEDURE

A. Specular and Diffuse Reflection

Arrange the experiment as shown in Figure 21 with the display tank near the laser and a mirror on a pivot mount arranged so as to reflect the beam back into the tank. It will be observed that near the mirror the reflected beam has approximately the same intensity as the incident beam. You might, however, observe a loss of intensity as the incident and reflected beams traverse the fluid. This is due to scattering of the beam by the fluid molecules, the process which makes the beam visible from the side.

Figure 20

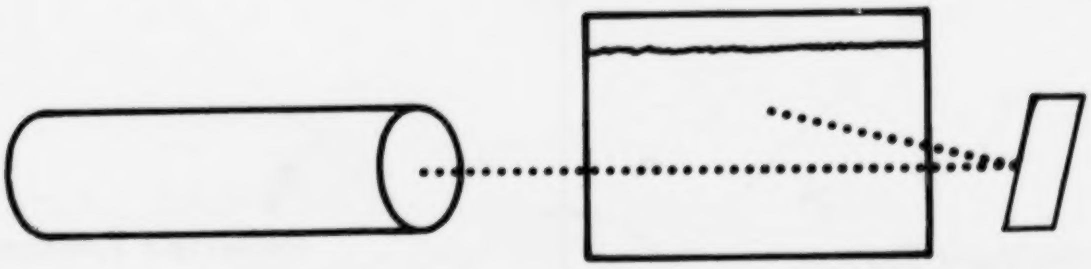


Normal
θ_i
θ_r
Incident Photon Flux
Reflected Photon Flux

$\theta_i = \theta_r$

LAW OF REFLECTION

Figure 21



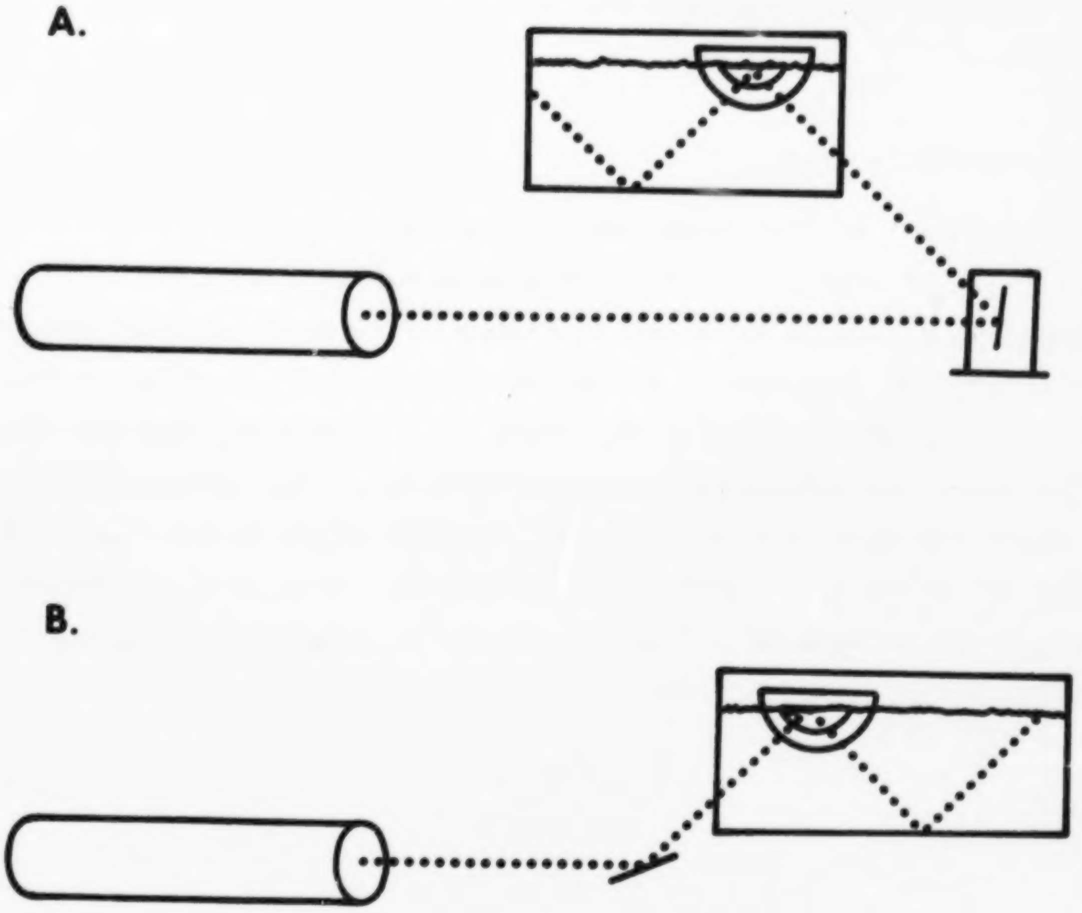
SPECULAR AND DIFFUSE REFLECTION SETUP

Hold a piece of white paper in front of the mirror. The light will now be diffusely reflected and no beam will be seen re-entering the display tank. The point at which the light strikes the paper will be visible through a wide angle, because of this diffuse reflection. When the paper is removed, the reflected beam will again be visible in the display tank. The point at which the laser beam strikes the mirror will not be readily apparent from the side since the light is being specularly reflected. Whatever light is seen from the side is caused by diffuse reflection from small random mirror imperfections and to scattering of dust on the mirror surface.

B. Law of Reflection

The second part of this experiment illustrates the Law of Reflection which shows that the angle of reflection always equals the angle of incidence. Arrange the apparatus as shown in Figure 22 (A or B) so that the laser beam enters the tank and is reflected off the upper surface of the display fluid. Using the surface of the fluid as a reference, measure the angles of incidence and reflection with a protractor. Now change the angle of incidence and measure angles again. At some angle termed the critical angle, the light will cease to be reflected. This critical angle concept is explained in more detail in Experiment 4, page 69, in the section on total internal reflection.

Figure 22



COMPARING ANGLES OF INCIDENCE AND REFLECTION

EXPERIMENT 4 -- REFRACTION OF LIGHT

Explanation:

In the previous experiment we observed that light travels in straight lines and is reflected at the interface between two media according to the law of reflection. Another property of light is that its velocity depends upon the medium in which it travels. This phenomena results in the refraction or "bending" of the light wave front as it passes obliquely from one substance into another. The ratio of the velocity of light in one medium to its velocity in a second medium is defined as the index of refraction (η).

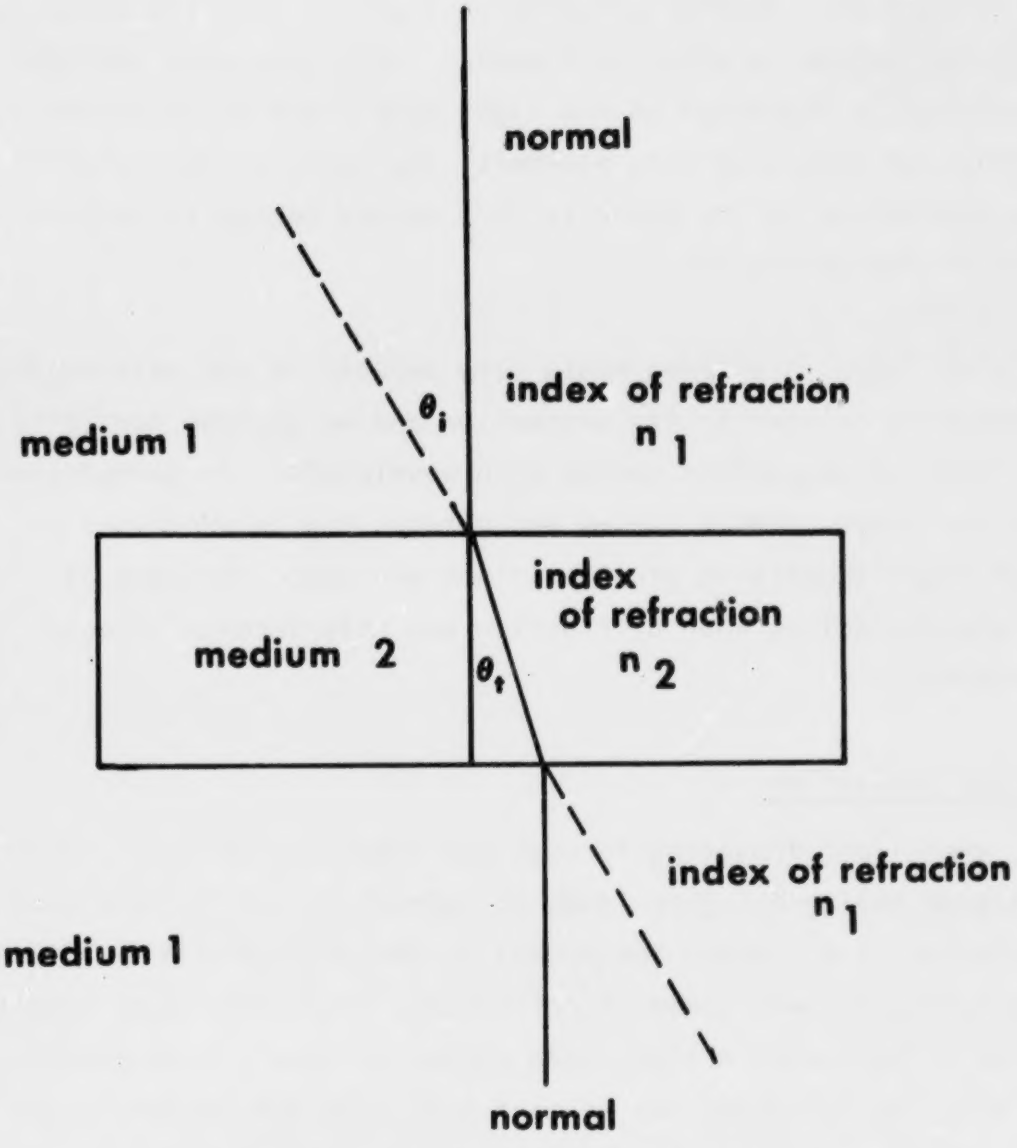
The velocity of light in a given media also depends on its wavelength. This dependence is related to its dispersion and we account for it by saying the index of refraction varies with wavelength. In geometrical optics, all the properties of lenses and mirrors can be explained by knowing that light travels in straight lines and obeys the laws of reflection and refraction when diffraction and interference effects can be neglected.

Total Internal Reflection

In general, when light traveling through one substance obliquely enters a second substance having a higher index of refraction, it is bent toward the perpendicular, i.e. toward the normal to the surface. When it enters a substance having a lower index of refraction, it is bent away from the perpendicular. Thus, when a light beam passes obliquely from water or glass into air, the refracted ray is bent away from the perpendicular as shown in Figure 23. The relationship between the angles and indices of refraction is given by Snell's law,

$$\eta_1 \sin\theta_i = \eta_2 \sin\theta_t$$

Figure 23


normal
θ_i
index of refraction
n_1
medium 1
index
of refraction
n_2
medium 2
θ_t
index of refraction
n_1
medium 1
normal

LAW OF REFRACTION

where:

n_1 = index of refraction of medium 1 with respect to a vacuum

n_2 = index of refraction of medium 2 with respect to a vacuum

θ_i = angle of incidence

θ_t = angle of refraction

As the angle of incidence θ_i increases, the angle of refraction θ_t increases to a value where the refracted beam just grazes the surface of the interface between the two materials. The angle of incidence $_i$ which produces an angle of refraction θ_t of 90° is called the critical angle. For a water and air interface, the critical angle is about 49 degrees. If this critical angle is exceeded, the beam does not leave the material at all but is instead totally reflected internally.

Since the index of refraction of air with respect to a vacuum is 1.0 the index of refraction of water with respect to a vacuum is 1.33, the relative index of refraction of air with respect to water (i.e. for a light ray going from water into air) is about 0.75. The critical angle for a water-air interface is therefore 48.6° as is shown in the calculation below:

$$n_w \sin \theta_{iw} = n_a \sin \theta_{ta}$$

$$n_w \sin \theta_{iw} = n_a \sin 90^\circ$$

$$1.33 \sin \theta_{iw} = 1 \sin 90^\circ = 1$$

$$\sin \theta_{iw} = 0.75$$

$$\theta_{iw} = 48.6^\circ$$

where:

n_w = index of refraction of water with respect to a vacuum

n_a = index of refraction of air with respect to a vacuum

θ_{iw} = angle of incidence of beam in water

θ_{ta} = angle of refraction of beam in air

Materials:

- Laser
- Display tank and fluid
- Mirror on pivot
- Protractor
- Ruler
- Thick slab of glass or other material
- Prism ($45^\circ - 45^\circ - 90^\circ$)

EXPERIMENTAL PROCEDURE

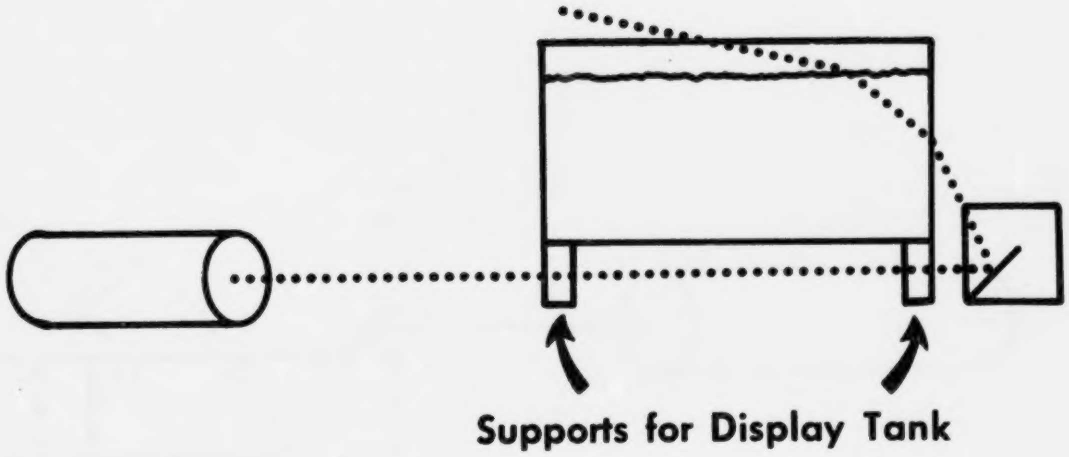
A. Refraction of light

In this first experiment, the relationship between the angle of incidence and the angle of refraction will be observed. Arrange the equipment as shown in Figure 24 using two large books or other objects to position the display tank above the laser beam. The beam should now pass under the tank, strike the mirror and be reflected into the display solution through the side of the tank. You will observe that the beam is bent toward the normal as it passes from a medium of low index of refraction to a medium of higher index (air to fluid) and is bent away from the normal as it passes from a higher index material to a lower index material (fluid to air).

Next, direct the laser beam into the display tank as shown in Figure 25. Use a book to support the laser if necessary. The beam will be reflected at the bottom and top of the fluid as it passes through the tank. Some small portion of the beam will escape the tank at each reflection point and will be refracted as it passes through the fluid-air interface. Measure the separation between two adjacent emerging beams. The index of refraction can then be calculated using the formula

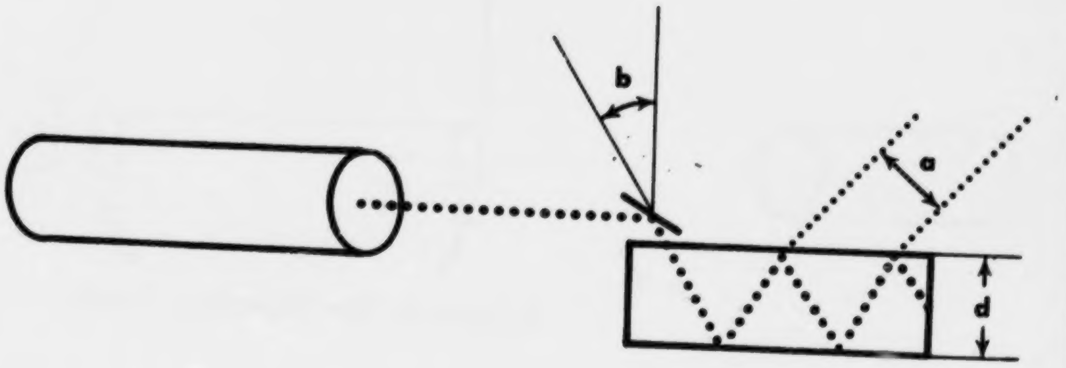
$$a = \frac{2d \sin \theta_i \cos \theta_i}{\sqrt{n_2^2 - \sin^2 \theta_i}}$$

Figure 24


Supports for Display Tank

OBSERVING LAW OF REFRACTION

Figure 25



DETERMINING INDEX OF REFRACTION

where:

a = the lateral separation of the rays leaving the tank
d = the thickness or depth of the display solution
n_2 = index of refraction of medium 2 with respect to a vacuum

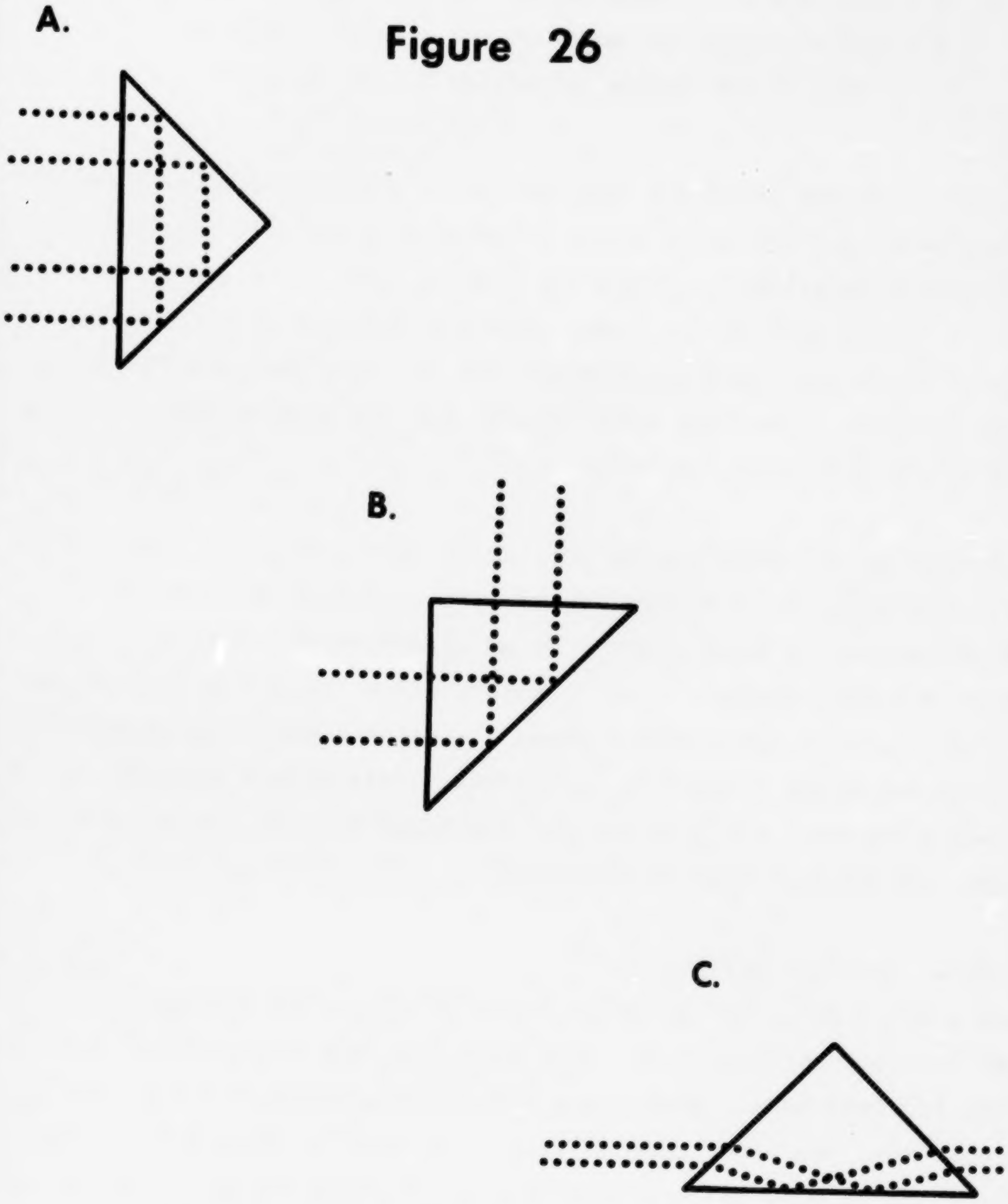
This principle has practical application in determining the index of refraction of a thick glass plate or other transparent material. To perform this experiment, remove the display tank and place a thick slab of glass in the path of the beam. Measure the separation between emerging beams and the angle between the incident beam and the normal to the surface. The above equation can then be used to calculate the index of refraction of the material.

The principle of refraction is utilized in all lenses for focusing by causing convergence or divergence of light. Refraction enables the lens of the eye to focus light from an object on the retina. This is a very important concept in laser safety since the energy density of the light beam is concentrated about a million times in passing through the lens and being focused on the retina. This effect accounts for the eye being the most critical part of the human body as far as potential damage from a laser beam is concerned.

B. Total Internal Reflection

Place a 45° - 45° - 90° prism as shown in Figure 26A to demonstrate total internal reflection of light back into the display tank parallel to the incident beam. Next place the prism as shown in Figure 26 B and note that the light beam is bent through 90°. This effect finds application in many optical instruments. Arrange the experimental setup as shown in Figure 26C. Observe that the beam transmitted through the prism rises as the incident beam is lowered. The line drawing in Figure 26C also illustrates how a right angle prism can be used to invert an image.

Figure 26



PRISM EXPERIMENTS

The critical angle of a prism can be measured by placing the prism on a pivot mount and rotating it so as to change the incident angle until total internal reflection occurs.

Total internal reflection can also be illustrated by using about 1-1/2 inches of solution in the display tank. Using the setup illustrated in Figure 24, adjust the angle of the incident beam until you obtain total internal reflection of the laser beam in the solution. This will occur when the incident angle is greater than the critical angle.

EXPERIMENT 5 -- POLARIZATION OF LIGHT

Explanation:

Electromagnetic radiation is, as the name implies, a combination of electric (E) and magnetic (H) fields. These fields are perpendicular to each other and to the direction of propagation of the radiation. The propagation of such electromagnetic radiation, of which light is one example, is depicted as a complex wave form as shown in Figure 27. In discussing polarization of light, it is customary to focus attention only upon the E field, since most common optical phenomena are due to the interaction of the E field of the radiation with the E field of physical structures. It is the E field, for example, that is photographically active and causes a chemical change in photographic plates.

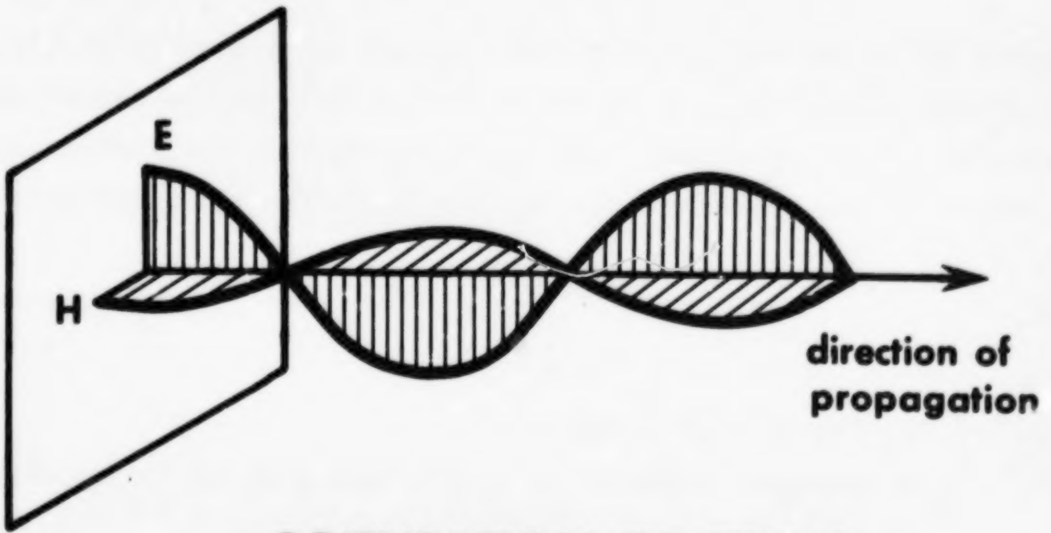
Light from most common sources is usually unpolarized. Light in these sources comes from an enormous number of individually oscillating atoms or molecules. The random orientation of these atoms and molecules results in a completely random orientation of the E fields of the various photons of light. If, however, some control is exercised over the orientation of the E field of a beam of light, the result is the production of polarized light.

Linearly Polarized Light

The electric field vector of a beam of light depends upon the sum of the individual E fields of the photons which comprise the beam. If the vector representing the E field of a beam of light always oscillates in a fixed plane as the beam progresses through space, the beam is said to be linearly polarized, or plane polarized (Figure 28).

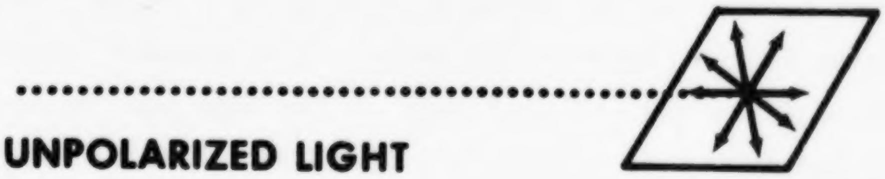
Linearly polarized light is most easily obtained through the use of a polarizing filter or polarizer. One such device consists of dichroic crystals of an iodine compound absorbed on a sheet of stretched polarized alcohol. The polarizer preferentially transmits light beam

Figure 27

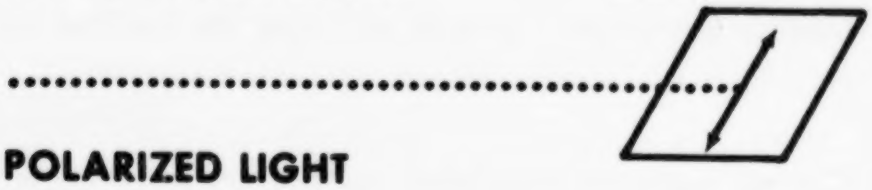

E
H
direction of
propagation

ORIENTATION OF FIELDS

Figure 28



A. UNPOLARIZED LIGHT



B. POLARIZED LIGHT

SCHEMATIC DRAWINGS

components whose E fields are aligned with the polarizing axis of the polarizer. Components whose E fields are not aligned with the polarizer are partially absorbed by the polarizer.

A second polarizer may be placed in the path of a beam which has already been linearly polarized, as shown in Figure 29. As the second polarizer is rotated, the intensity of the light transmitted by it will vary as the square of the cosine of the angle between the two polarizers.

$$I = I_o \cos^2\phi$$

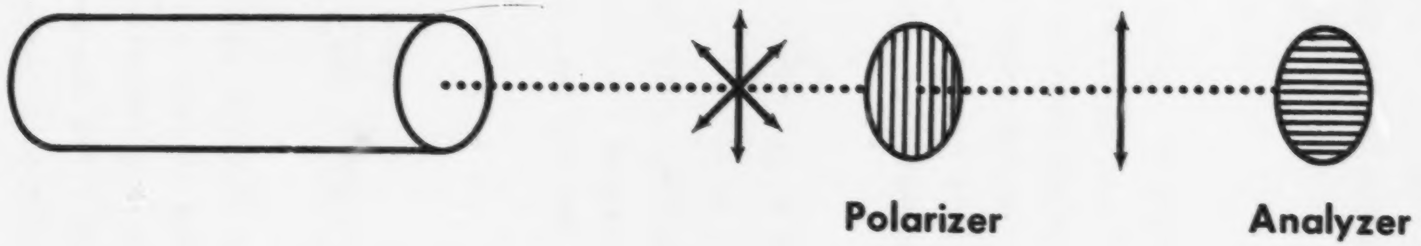
where:

I = transmitted intensity
I_o = maximum intensity of light impinging on the second polarizer
ϕ = angle between the axis of the two polarizers

A second means of producing polarized light is by reflection. When unpolarized light strikes a reflecting surface, there is found to be a preferential reflection for those photons whose E field lies in a plane perpendicular to the plane of incidence. (The plane of incidence is the plane determined by the incident path of the beam and the normal to the surface). Consequently, the E field of a beam of reflected light is strongly linearly polarized. A beam striking the surface at normal incidence will have all polarizations reflected equally.

At one particular angle of incidence, called the polarizing angle, no light will be reflected except that in which the E field vector is perpendicular to the plane of incidence. All light whose E field is not perpendicular to the plane of incidence is refracted into the material. At angles of incidence other than the polarizing angle, some of the components parallel to the plane of incidence are reflected so that, except at the polarizing angle, the reflected light is not completely linearly polarized.

Figure 29


Polarizer
Analyzer

POLARIZER—ANALYZER COMBINATION

Should linearly polarized light be directed at a reflecting surface it will be reflected or refracted, depending upon the orientation of the E field with respect to the plane of incidence. If the E field of the polarized light is aligned parallel to the plane of incidence, and the angle of incidence is equal to the polarizing angle, no light will be reflected.

The polarizing angle of a material, which depends upon its index of refraction, is that angle of incidence at which the angle between the reflected beam and the refracted beam is equal to 90°. This is illustrated in Figure 30. If n_1 is the index of refraction of the material in which the light is initially traveling, and n_2 is the index of refraction of the reflecting material, the polarizing angle ϕ is determined by

$$\tan \phi = \frac{n_2}{n_1}$$

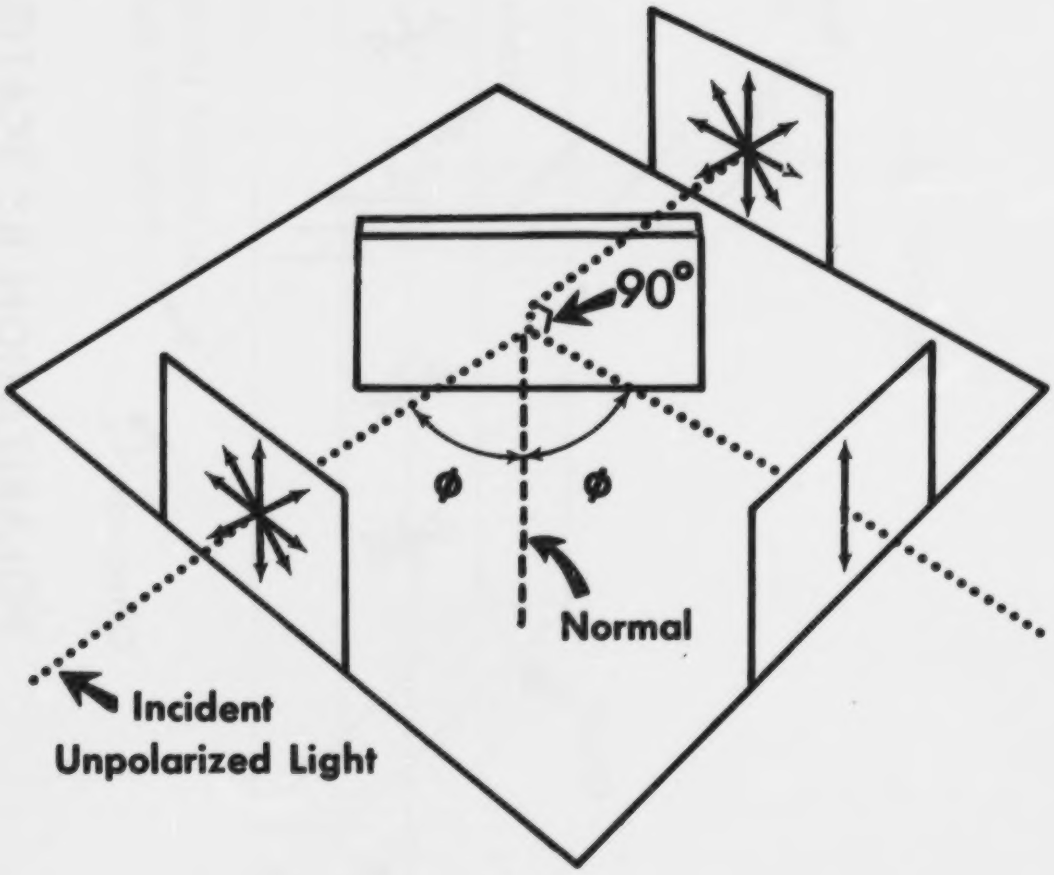
The polarizing angle is sometimes referred to as Brewster's angle, after Sir David Brewster who discovered the phenomenon in 1812. Brewster's angle can be obtained from Snell's law, given previously, by noting that

$$n_1 \sin \phi = n_2 \sin (\pi/2 - \phi)$$

$$\frac{n_2}{n_1} = \frac{\sin \phi}{\sin (\pi/2 - \phi)} = \frac{\sin \phi}{\cos \phi} = \tan \phi$$

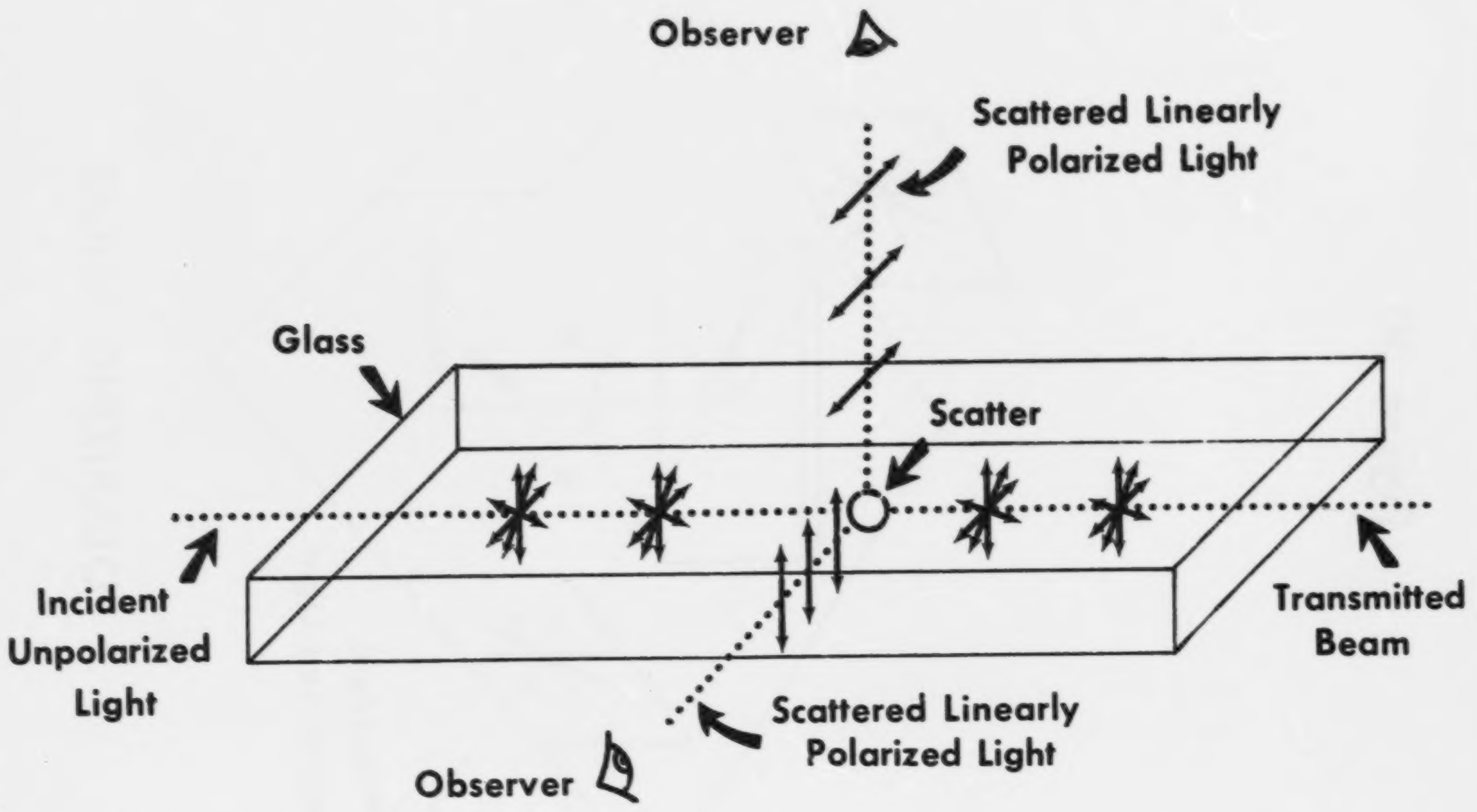
A third method of producing linearly polarized light is by scattering. When unpolarized light passes through a transparent material such as glass or air, the E field of the radiation sets the electric charges of the molecules in oscillation. The charges oscillate in every direction perpendicular to the direction of propagation of light. The charges re-radiate the light and the E field of the re-radiated light lies in a plane perpendicular to the direction of propagation of the original beam. An observer, looking perpendicularly at a beam of light passing through a piece of glass sees linearly polarized light. This is illustrated in Figure 31.

Figure 30


90°
ø
ø
Normal
Incident
Unpolarized Light

POLARIZING ANGLE

Figure 31


Observer
Scattered Linearly Polarized Light
Glass
Scatter
Incident Unpolarized Light
Transmitted Beam
Scattered Linearly Polarized Light
Observer

POLARIZATION BY SCATTER

Circular Polarization

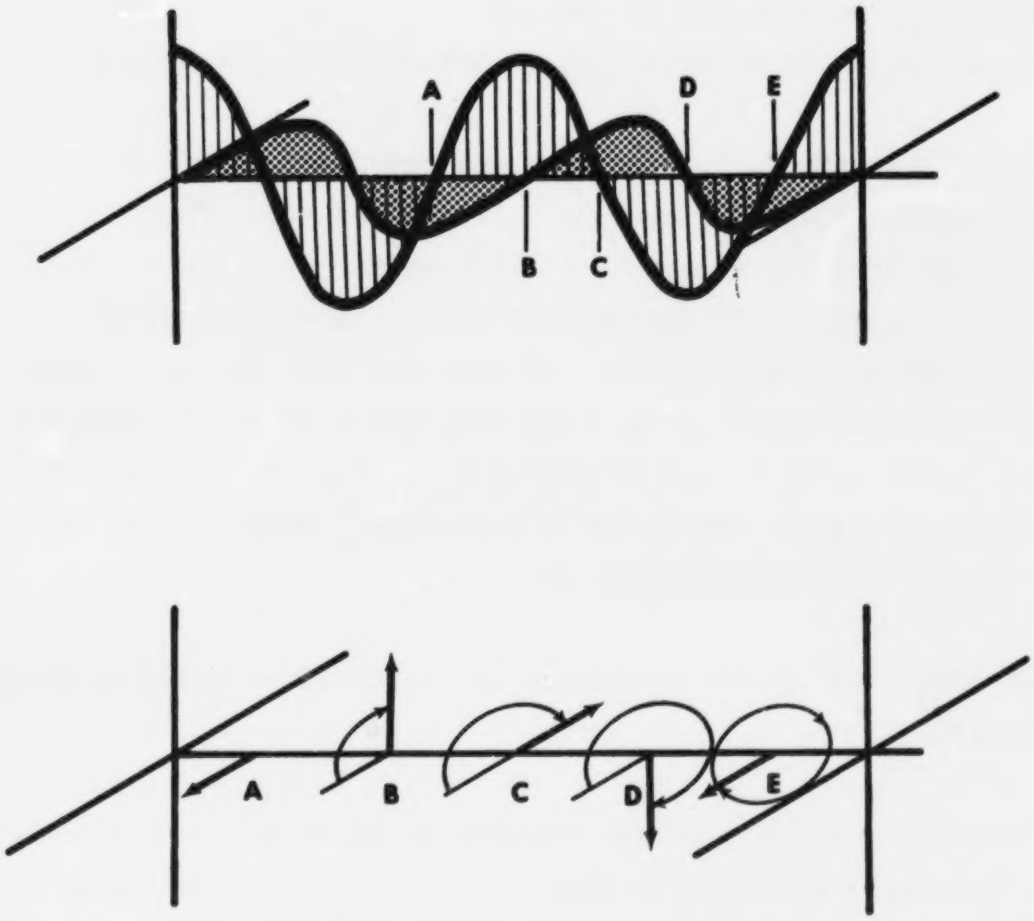
Consider two plane polarized, coherent beams of light of equal frequency and amplitude, whose planes of polarization are mutually perpendicular. The amplitudes of these vibrations can be drawn and the resultant vector plotted. If this is done, it will be seen that the resultant vector describes a linearly polarized beam whose plane of vibration lies at an angle of 45° to the plane of each of the component beams. (Conversely, a linearly polarized beam may be resolved into a pair of linearly polarized beams whose planes of polarization are mutually perpendicular.)

Next consider the above situation when one component is 90° out of phase with the other as shown in Figure 32. If the resultant vector is drawn, it will be seen that the magnitude of this vector will always be the same but the direction will change with time. Let E_z represent the magnitude of the resultant vector. If the resultant vector is drawn through a stationary point lying along the direction of propagation, the vector will sweep out a circle of radius E_z as the waves pass. This 90° phase difference between two linearly polarized coherent equal magnitude beams is called circular polarization.

When other than a 90° phase difference exists, this is known as elliptical polarization.

Circularly polarized light can be produced by using a doubly refracting crystal. A doubly refracting crystal displays many unusual properties. A beam of light passing through such a crystal is split into two components, each linearly polarized, but with their axes of polarization mutually perpendicular. Furthermore, the two components do not travel at the same speeds. Thus, if coherent light is directed into the crystal, the two components are out of phase when they emerge from the crystal. The amount of phase difference is proportional to the thickness of the crystal.

Figure 32


A
D
E
B
C
A
B
C
D
E

ELIPTICAL POLARIZATION

A crystal which causes a 90° difference in phase is called a quarter wave plate. This phase difference can be demonstrated by using one or more polarizing filters and the beam from a He-Ne laser. The beam should be checked for polarization using one of the polarizing filters. If a linearly polarized coherent beam of light is directed at a quarter wave plate, with the plane of polarization of the beam at a 45° angle to the optical axis of the crystal, the crystal will resolve the beam as described above. The beam leaving the crystal will consist of two linearly polarized components whose planes of polarization are mutually perpendicular and whose phase difference is 90° and can be raferred to as circularly polarized light. When a second polarizing filter, the analyzer, is slipped into the path of the beam, as shown in Figure 33, it will be noted that the light transmitted through the filter does not change in intensity as the analyzer is rotated.

Note: It must be noted that a given quarter wave plate is designed for use with a specific frequency of light. A quarter wave plate for green light is not a quarter wave plate for red light. Also note that the quarter wave plate must be of doubly refracting crystal, not of glass.

Materials:

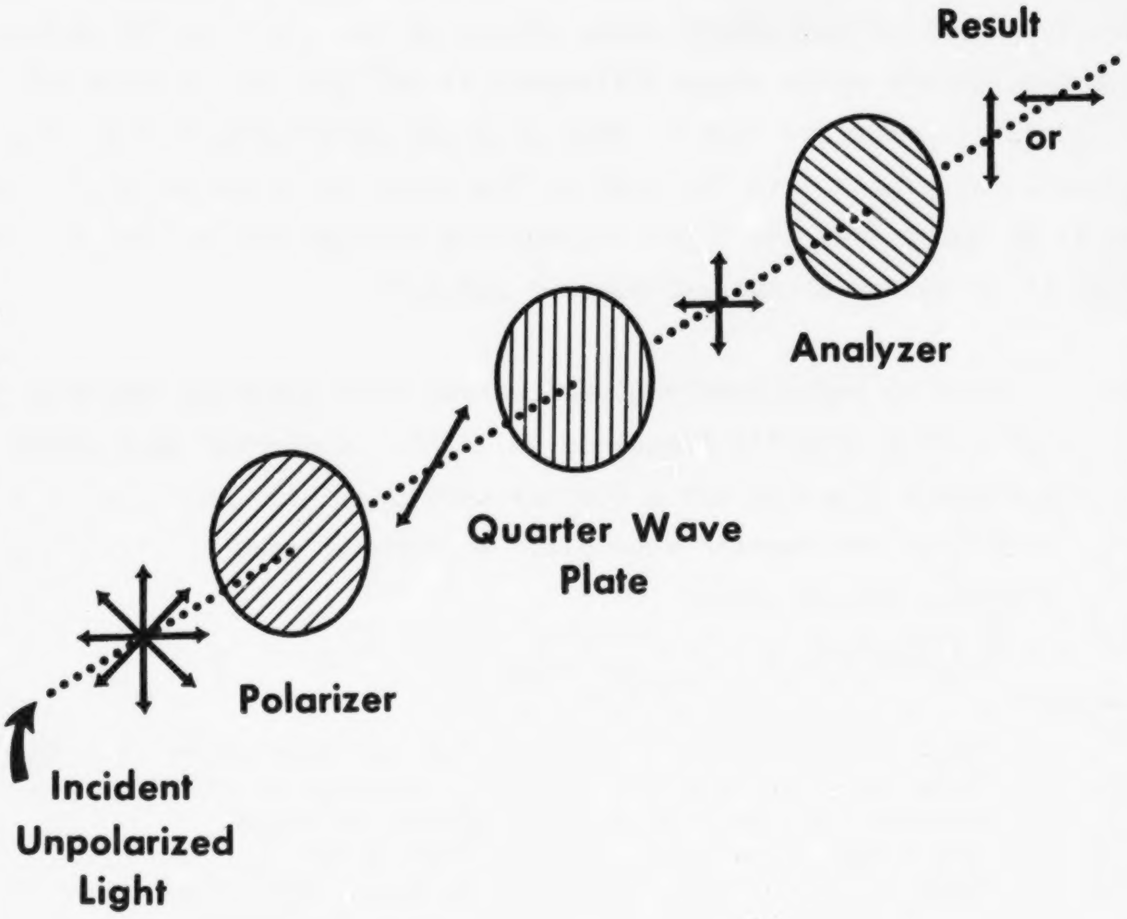
- Laser
- Polarizing filters (3)
- Display tank and fluid
- Small test tube
- $AgNO_3$
- Quarter wave plate (2) (Doubly refracting) (Red)
- Piece of glass
- Protractor
- Detector (CdS light meter with red filter)

EXPERIMENTAL PROCEDURE

A. Linear Polarization with Polarizing Lenses

Project the laser beam into the display tank and insert a polarizer into the path of the beam so that it can be rotated in the plane perpendicular to the beam. By rotating the polarizer, find the angle for which the

Figure 33


Result
or
Analyzer
Quarter Wave
Plate
Polarizer
Incident
Unpolarized
Light

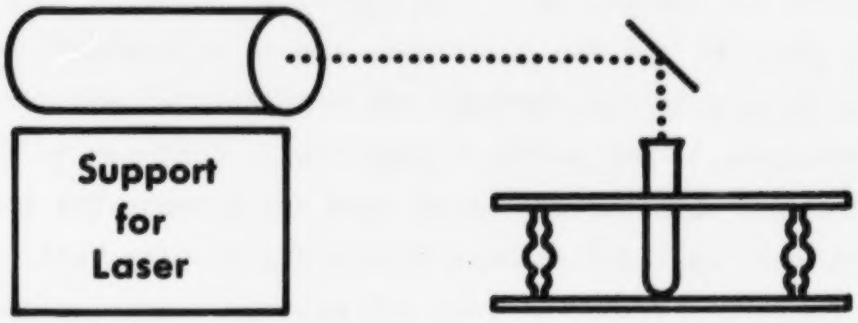
EFFECT OF QUARTER WAVE PLATE

beam is extinguished or is of minimum intensity. Note this angle and rotate the polarizer 90°. Next place a second polarizer (analyzer) between the first polarizer and the display tank. Keeping the orientation of the first polarizer fixed, rotate the analyzer until you find an angle which extinguishes the beam. Record this angle and rotate the analyzer until the maximum intensity is transmitted. Record this angle. Continue to rotate the polarizer and note the angle for which the beam fades out again. What is the angle of rotation between the maximum and minimum intensity? Define the angle of rotation at maximum intensity as zero. The angle for minimum intensity will then be 90°. Place a detector in the path of the transmitted beam and record the intensity and angle of rotation as the analyzer is rotated from the point of minimum to maximum intensity. Plot the transmitted intensity versus the square of the cosine of the angles of rotation from 0° to 90°. In this position the two polarizers are in a "crossed" position. Next, place a third polarizer between the original two and rotate it, noting that the beam is now partly transmitted. Continue to rotate the third polarizer and note the angles of rotation between the minimum and maximum of transmitted light as observed in the display tank. What is the angle of rotation between minimum and maximum transmission? What is the orientation of this third polarizer with respect to the other two when it is rotated to the position for maximum transmission of light?

B. Polarization by Scatter

Place a few drops of $AgNO_3$ in a small test tube of tap water to obtain a slightly "milky" solution of microscopic colloidal particles. Arrange the experimental setup as shown in Figure 34 so that the laser beam is directed into the top of the tube and travels down its long axis. Observe the scattered light through a polarizing filter. The fact that this scattered light is highly polarized can be observed by holding a polarizing filter at right angles to the direction the laser beam is traveling and rotating it. Repeat this experiment using a few drops of homogenized milk in a test tube of water. In this case, it will be observed that the scattered light is not polarized.

Figure 34


Support
for
Laser

OBSERVING
POLARIZATION BY SCATTER

C. Brewster's Angle

Arrange the equipment as shown in Figure 35 A. Place a slab of glass on top of a thick book and align it so the laser beam strikes the glass perpendicularly. Now rotate the glass until the angle of incidence is about 57°. The reflected beam should be stopped by using a sheet of paper as a screen for classroom visibility. Now insert a polarizer into the path of the beam between the laser and the glass. Rotate the polarizer until the angle is found for which the beam strikes the glass and the reflected beam disappears.

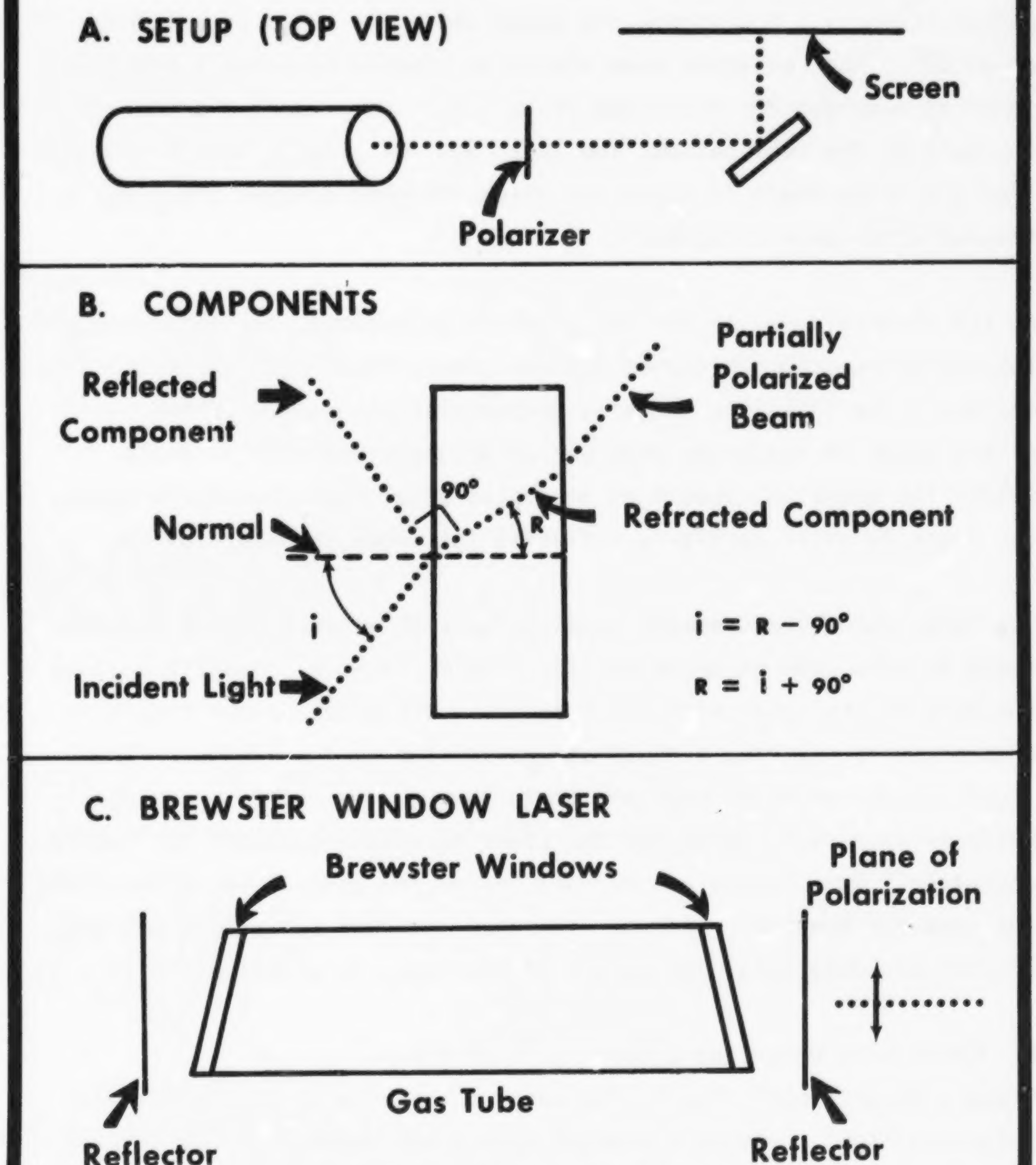
As the polarizing angle for the glass is approached, the intensity of the reflected beam diminishes and the transmitted light increases to a maximum. The intensity actually varies with the square of the cosine of the angle of deviation from the polarizing (Brewster's) angle. Rotate the glass and show that at angles other than Brewster's angle, the light is still partially reflected (as shown in Figure 35 B).

Gas laser tubes are commonly constructed with windows at the Brewster angle at both ends as shown in Figure 35 C. A wave propagating along the axis of the laser with its E field in the plane of the figure is completely transmitted without any reflection by the windows. The light can be reflected back and forth through the cavity by using external mirrors to establish the standing waves necessary for laser operation. Some lasers use mirrors inside the glass tube, eliminating the need for Brewster windows. If these internal reflectors are made of dichroic materials, the output of the laser is polarized.

D. Circularly Polarized Light

Place a polarizing filter in the path of the beam to obtain linearly polarized light. Insert a quarter wave plate between the polarizing filter and the display tank so that the polarization axis of the beam is at a 45° angle to the optical axis of the plate. Arrange the equipment as shown in Figure 33.

Figure 35


A. SETUP (TOP VIEW)

B. COMPONENTS

C. BREWSTER WINDOW LASER

Screen
Polarizer
Reflected Component
Partially Polarized Beam
90°
Normal
R
Refracted Component
i
Incident Light
i = R − 90°
R = i + 90°
Brewster Windows
Plane of Polarization
Gas Tube
Reflector
Reflector

BREWSTER'S ANGLE

Place a second polarizer (analyzer) filter between the quarter wave plate and the tank and rotate the analyzer. There should be no change in intensity.

Place a second quarter wave plate between the first quarter wave plate and the analyzer. When the axes of the two plates are parallel, it will be observed that the transmitted light is plane polarized and perpendicular to the original plane of polarization.

E. Unpolarized Light

Place a sheet of waxed paper into the path of the laser beam between a pair of polarizers and rotate the second polarizing filter. The transmitted intensity does not change with the angle of the second polarizer.

EXPERIMENT 6 -- COHERENCE

Consider an ideal elementary sinusoidal wave form. The characteristics of this wave are its amplitude A (its height above the zero line) and its wavelength λ (the distance from wave peak to wave peak). In this case, the amplitude varies with time in a constant sinusoidal manner and with the maximum remaining the same. The wave length also remains constant, as the wave propagates (Figure 36).

Temporal Coherence

The definition of coherence involves two or more waves rather than just one. Consider two waves, one superimposed over the other on the same line of propagation. (Figure 37 shows the two waves with the superimposition modified for clarity.)

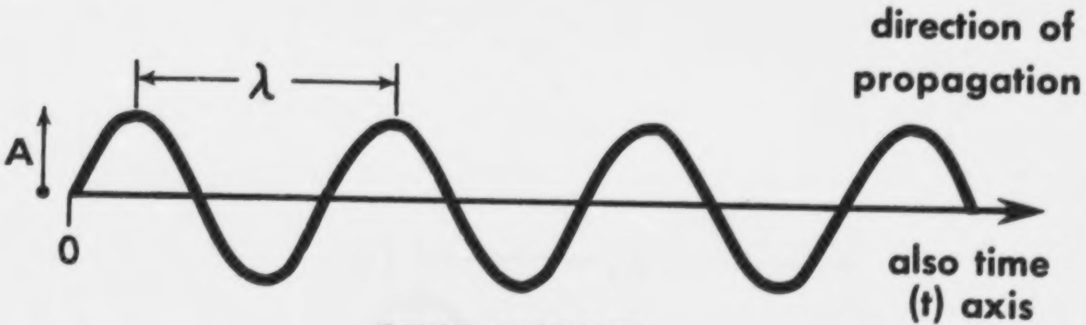
First, disregard the amplitudes of the points and consider points only with respect to the direction of propagation.

During a time t, each of the two waves advances down the line of propagation to a wave peak, point 1 on wave A_1 and point 2 on wave A_2. They are traveling at the same speed and have the same wavelength and, if allowed to continue, the wave peaks will occur at the same places all the way down the line. These waves are said to be in phase and coherent. This particular coherence, that is, with respect to time, is called temporal coherence.

With this in mind, we can now define coherence. Two or move waves are said to be coherent if the "phase difference" between two pairs of points, one on each wave, remains constant. In our example, where the waves are in phase, the phase difference is zero throughout and thus constant.

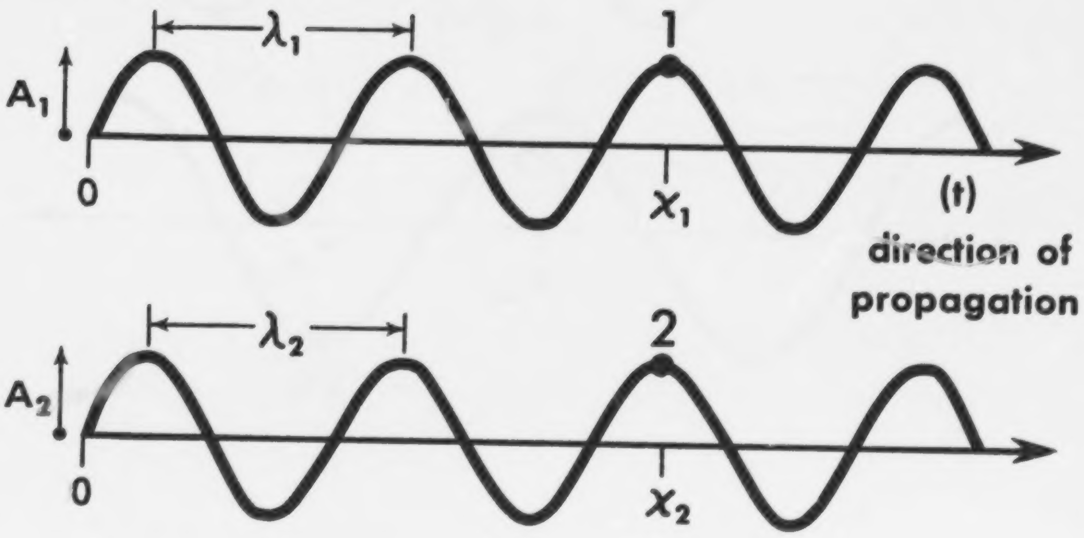
Figure 38 shows a slightly different situation. In this case, one wave "lags" the other slightly, but the waves are still temporally coherent

Figure 36


direction of
propagation
λ
A
0
also time
(t) axis

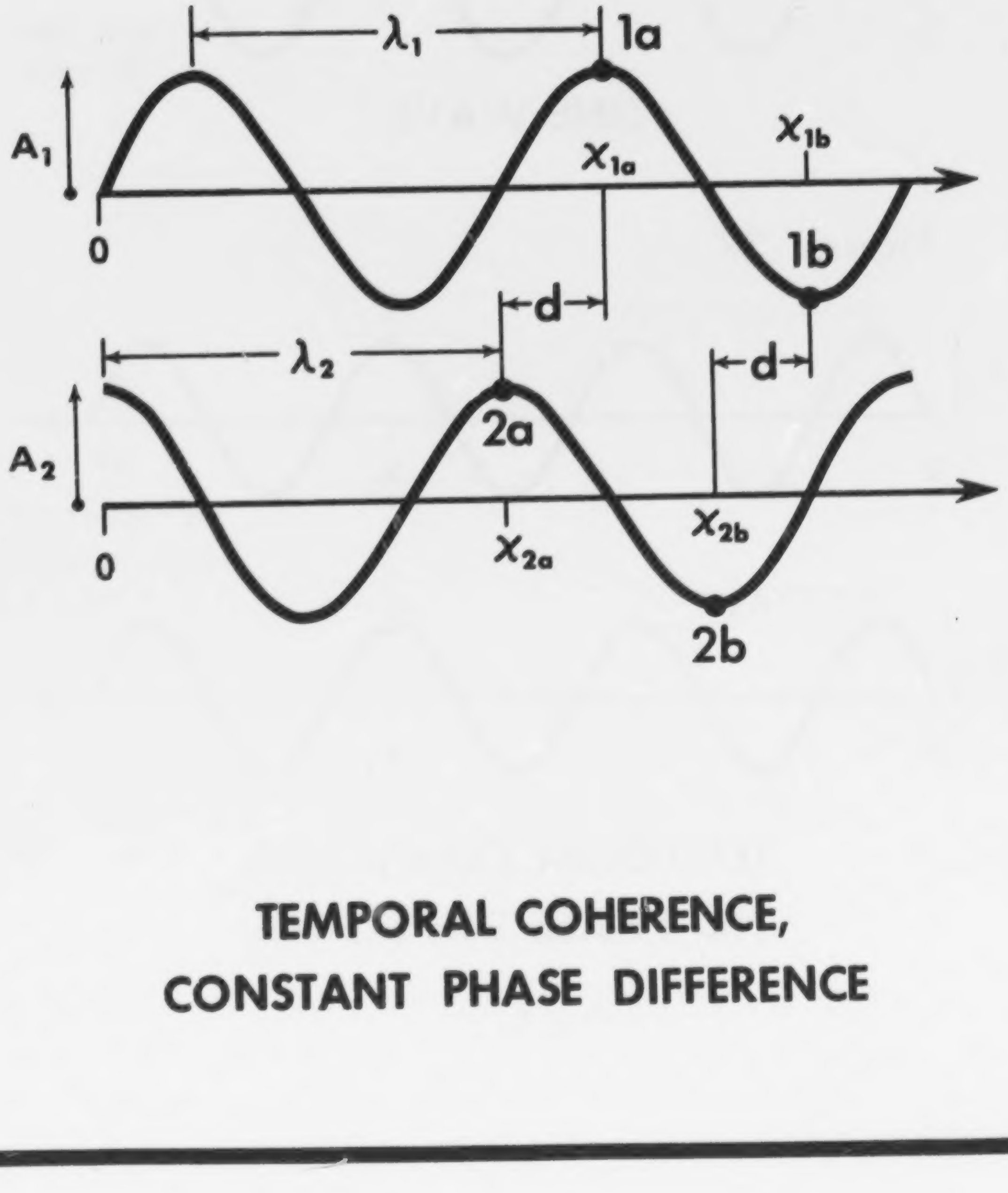
SINE WAVE

Figure 37


λ1
1
A1
0
x1
(t)
direction of
propagation
λ2
2
A2
0
x2

TEMPORAL COHERENCE,
NO PHASE DIFFERENCE

Figure 38


λ_1
1a
A_1
x_{1a}
x_{1b}
0
1b
d
λ_2
d
2a
A_2
0
x_{2a}
x_{2b}
2b

TEMPORAL COHERENCE,
CONSTANT PHASE DIFFERENCE

because the sets of points remain at a constant distance d apart along the line of propagation. They are not in phase but have a constant phase difference.

Interference

Up to this point, the amplitude of the waves being discussed has been ignored in order to point out other factors.

Consider two waves superimposed on each other along the same line of propagation. It is well known that as a wave moves through a media, it propagates a disturbance along the direction of propagation. The amount of disturbance depends on the amplitude of the wave. When the amplitude is positive (i.e. when a peak is formed or the wave point is moving up), it is termed positive disturbance. Alternately, when the amplitude is negative, it is termed negative disturbance.

If two waves are superimposed on one another along the same line of propagation, the amplitudes add. If there are two positive amplitudes, they total to a greater positive amplitude. Two negative amplitudes follow the same formula, adding to a greater negative amplitude. If, however, a negative amplitude is paired with a positive, the difference between the two is found for the total amplitude.

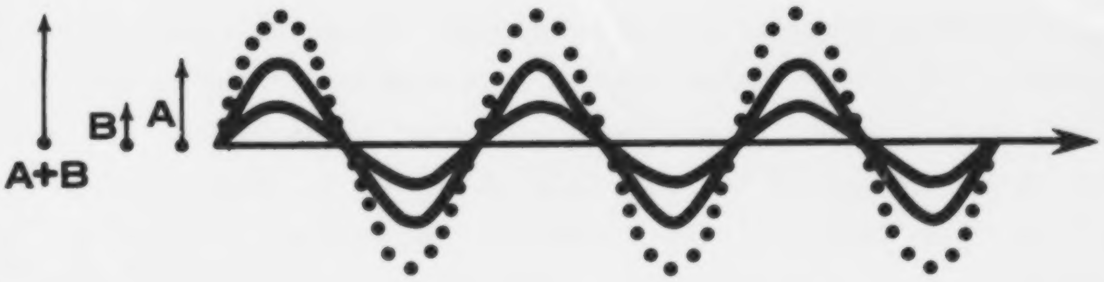
The interaction of two waves as described above is called interference. Constructive interference results from adding two wave amplitudes of the same sign (+ or -) (see Figure 39). Destructive interference results from adding two amplitudes of different signs (Figure 39).

Lateral Coherence

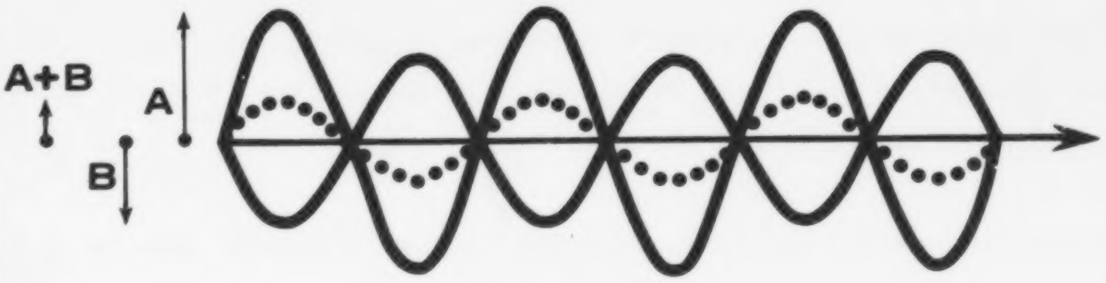
Consider two waves traveling along two parallel lines of propagation, with equal amplitudes, wave lengths, and in phase (Figure 40). Pick two points, one on each wave, and note what happens as the wave propagates.

Figure 39

A. Constructive

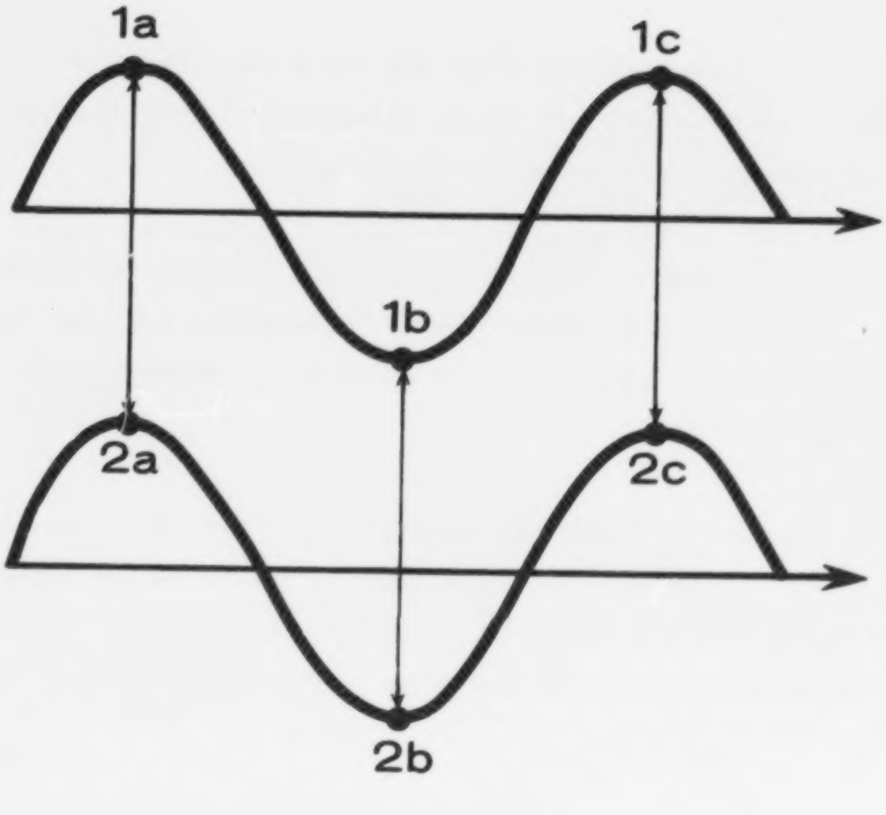


B. Destructive



INTERFERENCE

Figure 40


1a
1c
1b
2a
2c
2b

LATERAL COHERENCE

(It must be emphasized that only the positions of the points in a perpendicular direction to the line of propagation need be considered.) As the points move from A to B to C, the distance between them remains constant. The points are not only in phase along the path of propagation, but also in a direction perpendicular to the paths of propagation. Since these points are in phase perpendicular to the path of propagation, they are said to be laterally coherent.

Spatial Coherence

The discussion has been limited thus far to a two-dimensional representation. However, light waves are three-dimensional, and the concept of coherence must be expanded to cover such a system.

The transition is simple. Temporal coherence remains the same along the direction of propagation as does lateral coherence, but now lateral coherence is allowed to relate to any direction perpendicular to the line of propagation.

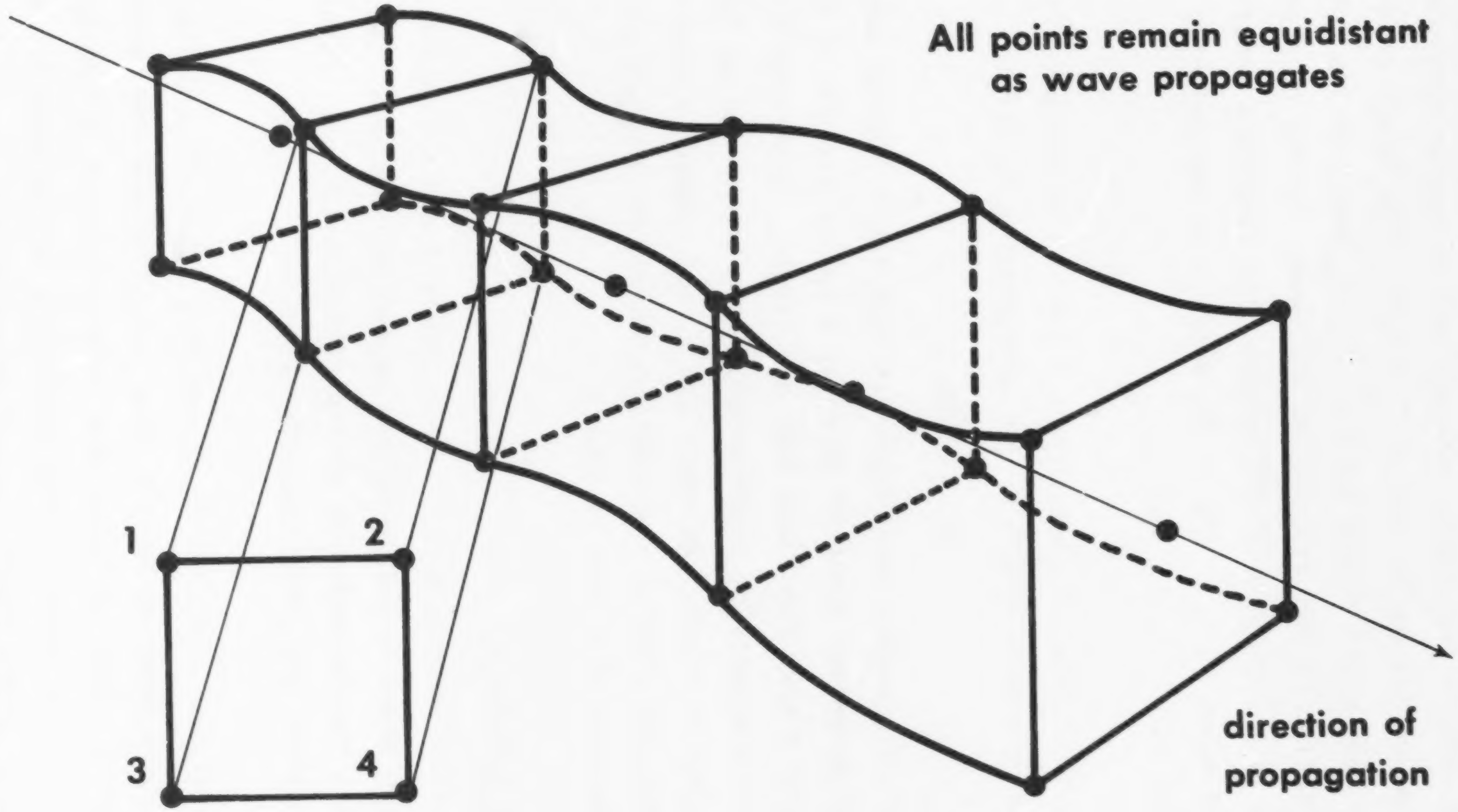
The result of combining these two concepts, lateral and temporal coherence, produces what is called spatial coherence in which two or more points are in phase a) along the direction of propagation (temporal); and b) along any direction perpendicular to the direction of propagation (lateral (Figure 41).

Degree of Coherence

Since coherence has been defined, degrees of coherence can be discussed. The question "How coherent is laser light, or any other wave form?" can be asked.

In nature, all waves contain components with wave lengths or frequencies both below and above the wave's primary frequency. In other words, they have a definite bandwidth B. This bandwidth determines the phase change that the wave can take and thus can be used as a measure of the wave's

Figure 41


All points remain equidistant
as wave propagates
1
2
3
4
direction of
propagation

SPATIAL COHERENCE

coherency. An approximation can be made to determine the time during which a wave remains reasonably coherent and is approximately equal to the reciprocal of the bandwidth, or $T_c \cong 1/B$. The length or distance over which a wave would remain coherent, then, would be the coherence time T_c multiplied by the velocity of the wave. In the case of light, the velocity is $c = 2.99774 \times 10^8$ m/sec. The coherence length L_c would then be equal to $L_c = v/B = c/B$, where v is the velocity of the wave and c the velocity of light.

To determine the number of wavelengths n over which the wave is coherent, we divide the coherence length by the wavelength n to obtain

$$n = c/B\lambda$$

The number of wavelengths over which the wave train remains coherent is the important parameter since it gives us a better picture of the quality of coherence of a wave than does time and length. Coherence time can be long for a low frequency of light or coherence length can be long for long wavelengths of light. We shall use n, the number of wavelengths over which the wave remains reasonably coherent, as our measure of the degree of coherence of a wave or source.

Importance of Coherence

We have said that laser light is highly coherent and have subsequently defined what is meant by coherence and degree of coherence. We shall now investigate the consequences of the coherency of laser light, the effects it produces and other characteristics.

The uses of ordinary light (which is not very coherent) are limited by two physical rules known as Abbe's sine condition and the second law of thermodynamics. Both of these were formulated well before coherent light was really considered. These conditions define both our ability to focus ordinary light and the amount of energy that can be transferred from a source of ordinary light to some material at another point in space.

Coherent light, however, is not subject to such restrictions. It can be focused into an extremely narrow beam, and onto a spot limited only by diffraction effects. In one form, the second law of thermodynamics states that when temperatures of the source and sink are equal, no further transfer of energy can take place. In this form, the law no longer applies to laser light; the temperature at the focused image of the laser can be made as high as the diffraction limitation allows.

Because of diffraction limited focusing, laser light can be focused down to a minimum cross-section of about one square wavelength. This leads to the possibility of attaining high energy density levels over extremely small areas.

One of the most startling consequences of coherent light was totally unexpected until the phenomenon was viewed for the first time during the operation of a continuous wave laser. This phenomenon is, of course, the speckled image produced when the highly coherent laser light is scattered from a semi-smooth diffuse reflector. Here we see diffraction and phase interference effects on a scale never attained before with visible light. What we see is really a stationary diffraction pattern in space resulting from the scattering of the coherent light by the diffuse reflector and the subsequent interference of the coherent wave trains with each other. The effect is enhanced by the high coherence so that the pattern extends to such dimensions visible to the human eye.

We should note, however, that this interference destroys the light's coherency a few wavelengths beyond the reflecting surface, just as such interference destroys coherency in ordinary light a few wavelengths beyond the source.

Since this phenomenon is so startling and has ramifications which carry through to nearly all uses of coherent light, we shall explain it in more detail.

First, let's look at ordinary light reflecting off a diffuse surface, this paper for example. The waves striking the surface of the paper are individually reflected by each tiny surface of the paper (according to the laws of reflection) and interfere with each other. Since coherence is very low, on the order of three wavelengths, the diffraction pattern produced is not only small (again on the order of a few wavelengths) but changes rapidly. The dimensions are so small that the human eye cannot resolve the phenomenon. With the highly coherent light produced by the laser (coherence length in the order of 10^{10} to 10^{14} wavelengths) visible interference occurs over a much larger volume and the resulting diffraction pattern is huge by wavelength standards. Also, due to long coherence time, the pattern changes relatively slowly and thus remains visible for longer periods of time. The net effect is the granular pattern we see when the laser light is reflected.

It is interesting to note also that the pattern viewed depends substantially upon the observer. The size of the individual grains of light we see is directly proportional to the iris size of the eyes. Also, if the observer remains stationary the pattern will remain stationary with little change except that due to instability of the laser.

Even more unusual, when the viewing system is defocused the pattern still remains sharp, although its shape changes.

The diffraction and interference effects which cause this phenomenen play an important role in any situation where the laser beam is reflected, transmitted, or reacts with matter in any way. Coupled with highly coherent light, they make possible such applications of the laser as holography and demonstration of many basic physical optics concepts.

EXPERIMENT 7 -- DIFFRACTION

Explanation:
Under appropriate experimental conditions it can be shown that light does not always travel in straight lines.

The term diffraction refers to phenomena in which light or other electromagnetic radiation is bent around an obstacle instead of exhibiting a simple straight line propagation predicted by geometrical optics.

The wave theory explanation of the interference and diffraction of light was first introduced by the English physician and physicist Thomas Young (1773-1829). He performed his double-slit experiment in 1801 to explain the waves' departure from straight line propagation. This concept was later developed by the Franch mathematician Augustine Fresnel (1788-1827), who gave it a strong mathematical foundation.

If light passes near the edge of an object, light and dark bands are seen in the region of the geometric shadow. The light can thus be "bent" around an opaque object. The light is bent (or diffracted) by obstacles, in a fashion similar to the way waves on water are bent around a pier in their path.

This discussion will cover only the general concepts of diffraction and interference since most text books present calculations of the principle characteristics of simple diffraction patterns.

According to Huygen's principle, when light emerges from an aperture or the edge of a barrier, each point along a plane perpendicular to the direction of propagation of the incident light may be regarded as a new source. The amplitude of the radiation from these new sources arriving at the viewing screen is dependent upon the distance from the new source to the point at which they strike the screen.

The summation of the interference of the light waves from a slit or barrier edge produces an illumination pattern of maximum and minimum intensity on the viewing screen. In the case of a slit, the spacing between regions of maximum and minimum intensity is inversely proportional to the width of the slit. A diffraction pattern of light from two slits is simply the interference pattern from the two slits superimposed on the diffraction patterns from the individual slits. An elaboration of the 2-slit idea includes the use of a number of slits equally spaced. Such an array is called a diffraction grating and the diffraction pattern obtained is the result of multiple interference of a large number of slits so that the maximum and minimum are much sharper than before.

NOTE:
Diffraction is an important phenomenon of light that has many applications when considering the use of lasers and laser safety. For example it is the diffraction phenomenon that sets a limit on the smallest spot size that can be focused on the retina of the eye and thus the maximum concentration of light or energy that can occur. Large particle scattering, which is a diffraction phenomenon, is also important when considering the potential hazards of high power lasers in the atmosphere.

Materials:
- Laser
- Single slit diffraction aperture
- Double slit diffraction aperture
- Circular diffraction aperture
- Transmission grating
- Razor blade

EXPERIMENTAL PROCEDURE

A. Single slit diffraction pattern

Place a single-slit aperture in the path of the laser beam. The diffraction pattern obtained with a single slit has a broad intense central maximum with subsidiary maxima on both sides, as shown in Figure 42. To analyze this phenomenon, imagine each point along the slit to be a source of waves which are in phase. Consider that the slit is divided into two zones, AB and BC. To begin with, let us consider only the waves that come out at an angle θ_n so that they all strike the viewing screen at the point P and are cancelled, producing a minima at that point, as shown in Figure 42. Since the screen is far away from the slit, it can be considered that the angle θ_n is approximately equal to θ_1 and θ_2. At an angle θ_n, a wave from point B travels a distance $\lambda/2$ further than a wave from point C. Similarly, a wave going from point A to point P travels $\lambda/2$ further than a wave from point B. Thus, the intensity at point P on the viewing screen will be zero since the waves arrive one with a crest and the other with a trough, resulting in the cancellation of one another. A similar cancellation will occur when the path difference of rays point A relative to those from point C is an integral number of wavelengths. Thus we can deduce from Figure 42 that subsequent nodes fall at P_n where

$$\sin\theta = n\lambda/d$$

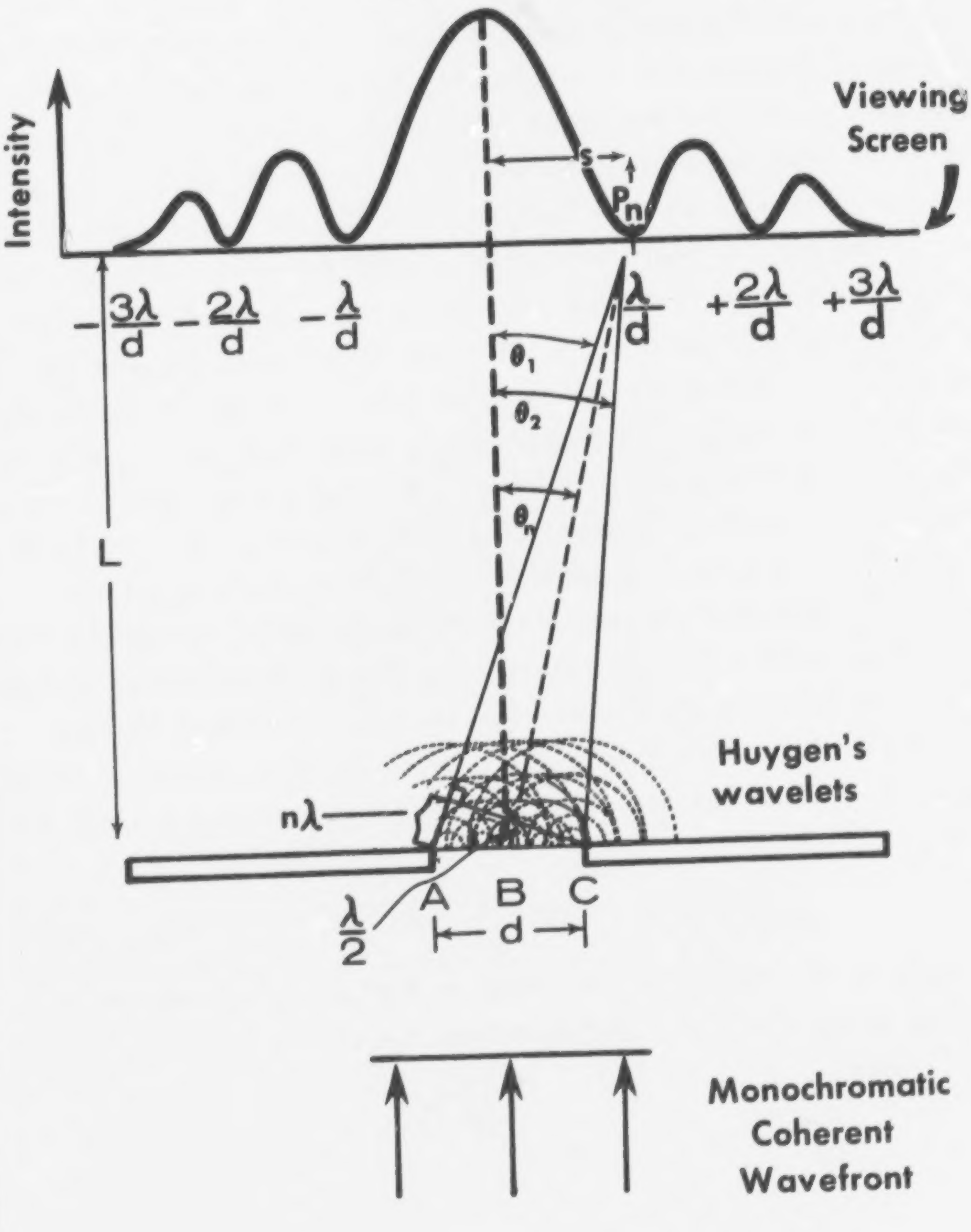
Since $\sin\theta$ is also equal to the ratio of distance L between the slit and the screen divided by the distance s from the central maximum to the first minimum, then:

$$s/L \simeq \frac{\lambda}{d}$$

$$s \simeq \frac{L\lambda}{d}$$

This is the spacing between successive minima. Thus, the wider the slit size is, the closer is the spacing between the nodes. Test this equation by using single slits of different widths.

Figure 42


Intensity
Viewing Screen
s
P_n
$-\frac{3\lambda}{d}$
$-\frac{2\lambda}{d}$
$-\frac{\lambda}{d}$
$\frac{\lambda}{d}$
$+\frac{2\lambda}{d}$
$+\frac{3\lambda}{d}$
θ_1
θ_2
θ_n
L
Huygen's wavelets
nλ
$\frac{\lambda}{2}$
A
B
C
d
Monochromatic Coherent Wavefront

SINGLE SLIT DIFFRACTION

B. Double slit diffraction pattern.

This experiment was originally performed by Thomas Young in order to demonstrate the effects to be expected from a wave description of light. In this experiment, we consider what happens when there is more than one slit.

Insert a double slit barrier in the path of the laser beam. Alternately expose first one and then both slits. When both slits are exposed, one obtains a combined interference and diffraction pattern, as shown in Figure 43. In this case, each of the two slits has a diffraction pattern. The diffraction pattern of each is on top of the other, causing an interference pattern on top of the diffraction pattern. Thus, we obtain an interference pattern (because of the two slits) which in effect modifies (modulates) the intensity distribution pattern of the single slit. That is, one obtains a lot of spots of equal intensity under the envelope formed by the diffraction pattern of each individual slit.

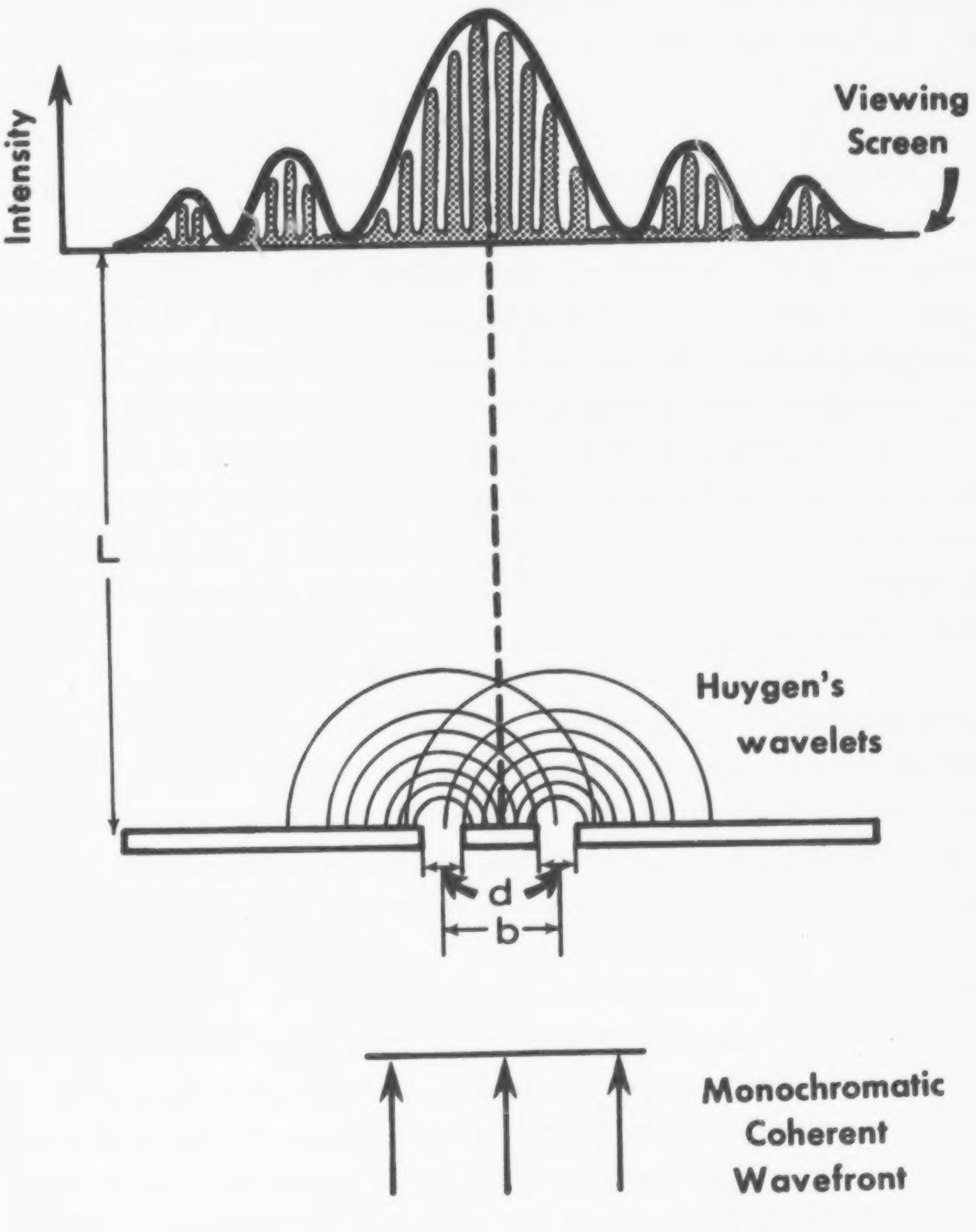
C. Diffraction grating patterns.

Substitute a simple transmission diffraction grating for the two slits. The grating may be considered as a general case of the double slit barrier. The diffraction maximum and minimum intensities are very sharp. Their spacing is given by the equation $\theta_n = n\lambda/d$.

D. Diffraction by a straight edge.

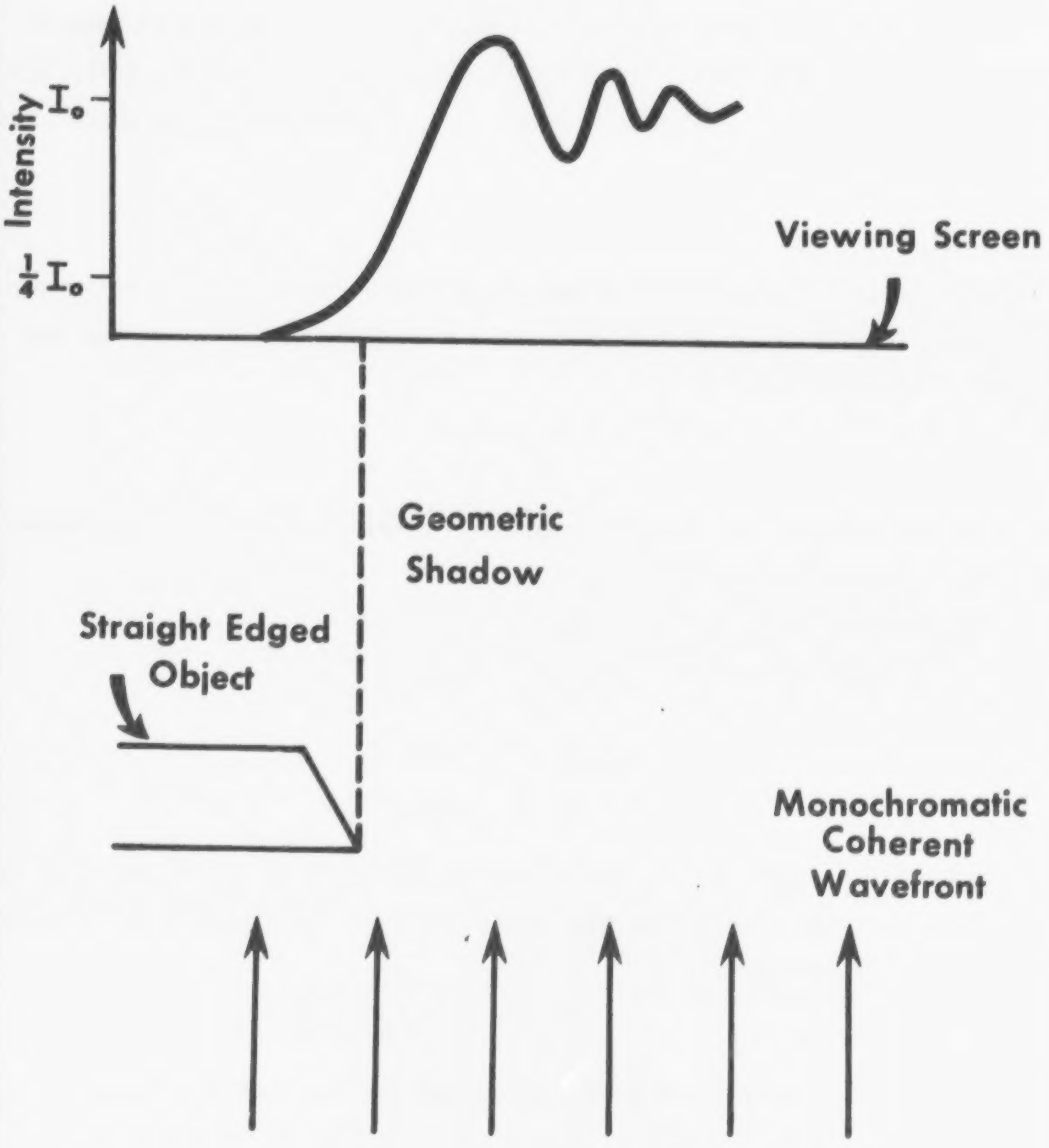
Position a razor blade in the path of the laser beam so that the sharp edge intersects about half of the beam. This will give rise to a diffraction pattern which is characterized by parallel bands of maxima and minima as shown in Figure 44. The intensity at the edge of the geometric shadow is about 1/4 of the undiffracted intensity. Beyond the geometric shadow, the intensity varies with position in an oscillatory way, giving rise to regular variations in brightness which gradually settle down to the undiffracted intensity.

Figure 43


Intensity
Viewing Screen
L
Huygen's wavelets
d
b
Monochromatic Coherent Wavefront

DOUBLE SLIT DIFFRACTION

Figure 44


Intensity
I₀
¼ I₀
Viewing Screen
Geometric Shadow
Straight Edged Object
Monochromatic Coherent Wavefront

DIFFRACTION BY A STRAIGHT EDGE

E. Circular aperture diffraction patterns.

Many optical systems have circular apertures. The diffraction pattern of such a system appears as a set of concentric circular rings, as shown in Figure 45. The calculation of the angles at which maxima and minima of illumination occur is more complicated and requires the use of Bessel functions. Since this is not a simple mathematical function, only the results will be given. For the single slit, the points of minimal intensity are given by:

$$\sin \theta_n = n\lambda/d$$

For the circular aperture with diameter d, the minimal intensity observed on a viewing screen at a distance L from the aperture is given by the formula:

$$\sin \theta_n = (K_n)(\lambda/d)$$

where n is an integer (1, 2, 3...) and K_n is determined by using Bessel functions. The values of K_n are:

$$K_1 = 1.22$$

$$K_2 = 2.23$$

$$K_3 = 3.24$$

$$K_4 = 4.24$$

If the diffraction pattern is projected on a screen at a large distance, L, from the circular aperture, the radii (r_n) of the circles of minimum intensity are given by:

$$\tan \theta_n = r_n/L.$$

For small angles, $\sin \theta$ is a good approximation for $\tan \theta_n$. Thus,

$$\sin \theta_n \approx r_n/L \quad \text{or} \quad r_n \approx L \sin \theta_n.$$

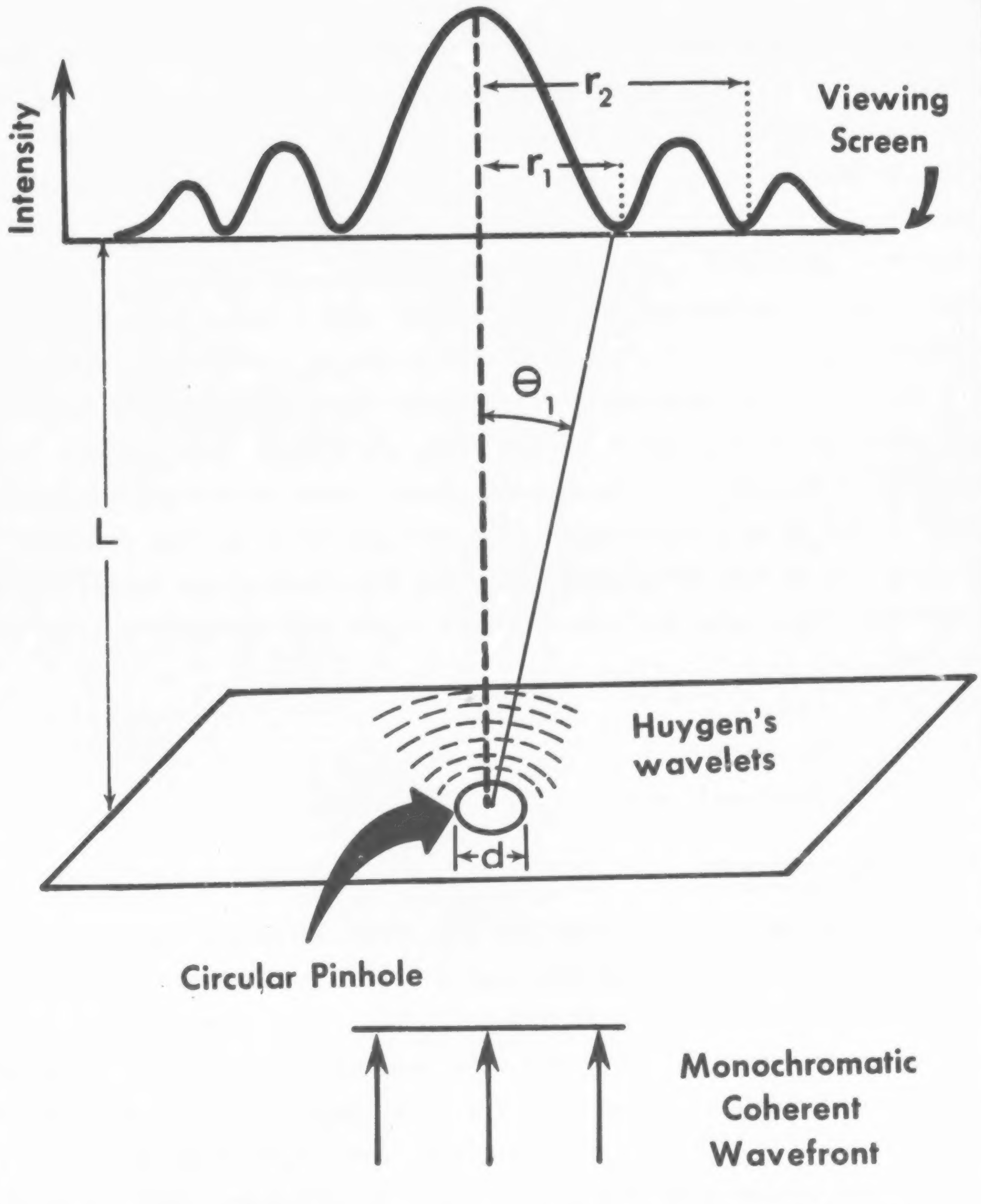
Thus the radius of the minimum intensity is given by:

$$r_n \approx (K_n)(\lambda/d).$$

Therefore, the first dark ring has a radius of $r_1 = 1.22\ L\lambda/d$ and a diameter $d_1 = 2.44\ L\lambda/d$.

The diffraction of light by a circular aperture is of special importance in laser safety because diffraction by the aperture of the eye (the iris) determines the smallest spot size that can be produced.

Figure 45


Intensity
r_2
Viewing Screen
r_1
Θ_1
L
Huygen's wavelets
d
Circular Pinhole
Monochromatic Coherent Wavefront

DIFFRACTION BY A CIRCULAR APERTURE

EXPERIMENT 8 -- HOLOGRAM

Explanation:
The preceding experiments in diffraction and interference provide the foundation for an understanding of the process of holography. The word "holography" comes from the Greek words "holos" meaning whole and "graphos" meaning writing. Thus, a hologram would be a picture of an object in its entirety. Holography is a technique for storing and reproducing the image of a three-dimensional object. It is formed by photographing the interference pattern produced when a laser beam that is scattered from an object interacts with a second reference laser beam. Since the reference beam and the scattered laser light have a definite phase relation at each point on the film, an interference pattern is formed and recorded. The three-dimensional image of the object is reconstructed by shining a laser beam through the film thus produced. It is because of the monochromaticity and the fixed phase relationships between the individual photons of laser light that holography is possible.

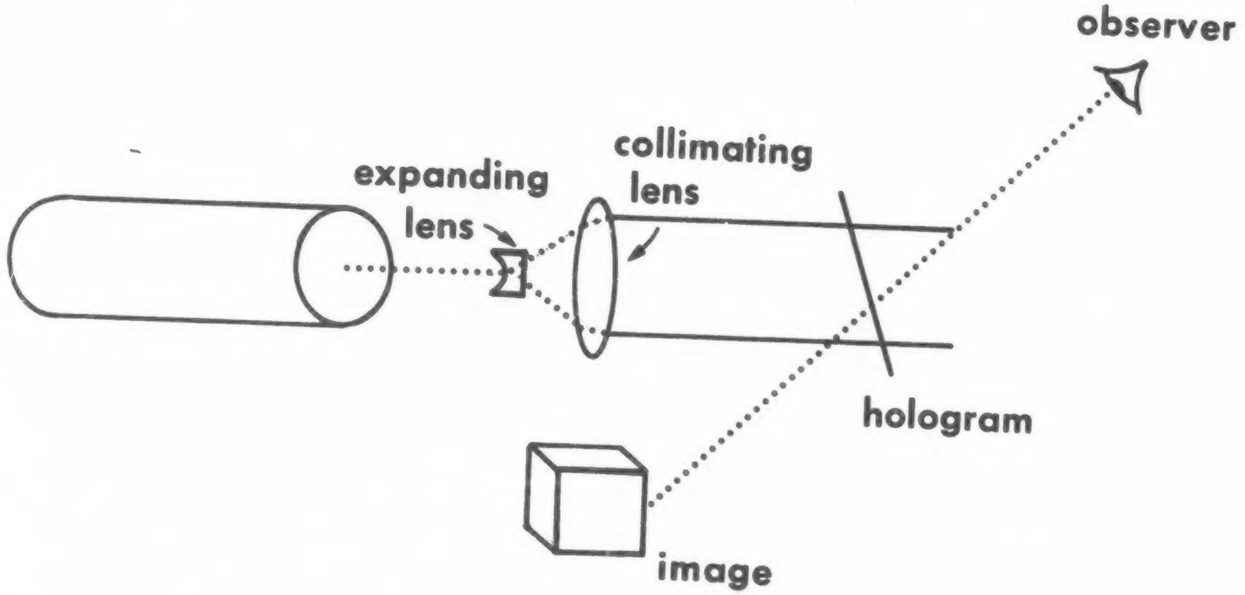
Materials: Laser
Hologram
Divergent lens

EXPERIMENTAL PROCEDURE

Place the divergent lens in front of the laser to spread the beam. Insert the hologram into the path of the beam at a point where the beam has diverged enough to cover the entire hologram. View from in front of the laser but do not look directly down the beam path (Figure 46). Now cover a portion of the hologram and note that the image is still complete, though reduced in clarity. This illustrates that the information contained by a hologram is recorded over the entirety of the hologram. Next, find the real image.

An alternate and perhaps safer method of viewing the hologram is to view from the laser side of the hologram, with the hologram held at a slight angle to the path of the beam. Much sharper images can be obtained with a collimated beam.

Figure 46


observer
expanding
lens
collimating
lens
hologram
image

VIEWING A HOLOGRAM

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